Handbook of Drought and Water Scarcity

Management of Drought and Water Scarcity

Edited by
Saeid Eslamian
Faezeh Eslamian

CRC Press
Taylor & Francis Group

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Editors

Saeid Eslamian is a full professor of hydrology and water resources engineering in the Department of Water Engineering at Isfahan University of Technology, where he has been since 1995. His research focuses mainly on statistical and environmental hydrology in a changing climate. In recent years, he has worked on modeling natural hazards, including floods, severe storms, wind, drought, pollution, water reuses, sustainable development and resiliency, etc. Formerly, he was a visiting professor at Princeton University, New Jersey, and the University of ETH Zurich, Switzerland. On the research side, he started a research partnership in 2014 with McGill University, Canada. He has contributed to more than 500 publications in journals, books, and technical reports. He is the founder and chief editor of both the *International Journal of Hydrology Science and Technology* (IJHST) and the *Journal of Flood Engineering* (JFE). Eslamian is now associate editor of three important publications: *Journal of Hydrology* (Elsevier), *Eco-Hydrology and Hydrobiology* (Elsevier), and *Journal of Water Reuse and Desalination* (IWA). Professor Eslamian is the author of approximately 150 book chapters and books.

Dr. Eslamian's professional experience includes membership on editorial boards, and he is a reviewer of approximately 50 Web of Science (ISI) journals, including the *ASCE Journal of Hydrologic Engineering, ASCE Journal of Water Resources Planning and Management, ASCE Journal of Irrigation and Drainage Engineering, Advances in Water Resources, Groundwater, Hydrological Processes, Hydrological Sciences Journal, Global Planetary Changes, Water Resources Management, Water Science and Technology, Eco-Hydrology, Journal of American Water Resources Association, American Water Works Association Journal,* etc. UNESCO has also nominated him for a special issue of the *Eco-Hydrology and Hydrobiology Journal* in 2015.

Professor Eslamian was selected as an outstanding reviewer for the *Journal of Hydrologic Engineering* in 2009 and received the EWRI/ASCE Visiting International Fellowship in Rhode Island (2010). He was also awarded outstanding prizes from the Iranian Hydraulics Association in 2005 and Iranian Petroleum and Oil Industry in 2011. Professor Eslamian has been chosen as a distinguished researcher of Isfahan University of Technology (IUT) and Isfahan Province in 2012 and 2014, respectively. In 2016, he was a candidate for national distinguished researcher in Iran.

He has also been the referee of many international organizations and universities. Some examples include the U.S. Civilian Research and Development Foundation (USCRDF), the Swiss Network for International Studies, the Majesty Research Trust Fund of Sultan Qaboos University of Oman, the Royal Jordanian Geography Center College, and the Research Department of Swinburne University of Technology of Australia. He is also a member of the following associations: American Society of Civil Engineers (ASCE), International Association of Hydrologic Science (IAHS), World Conservation Union

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Professor Eslamian finished Hakimsanaei High School in Isfahan in 1979. After the Islamic Revolution, he was admitted to IUT for a BS in water engineering and graduated in 1986. After graduation, he was offered a scholarship for a master's degree program at Tarbiat Modares University, Tehran. He finished his studies in hydrology and water resources engineering in 1989. In 1991, he was awarded a scholarship for a PhD in civil engineering at the University of New South Wales, Australia. His supervisor was Professor David H. Pilgrim, who encouraged him to work on "Regional Flood Frequency Analysis Using a New Region of Influence Approach." He earned a PhD in 1995 and returned to his home country and IUT. In 2001, he was promoted to associate professor and in 2014 to full professor. For the past 22 years, he has been nominated for different positions at IUT, including university president consultant, faculty deputy of education, and head of department.

Professor Eslamian has made three scientific visits to the United States, Switzerland, and Canada in 2006, 2008, and 2015, respectively. In the first, he was offered the position of visiting professor by Princeton University and worked jointly with Professor Eric F. Wood at the School of Engineering and Applied Sciences for one year. The outcome was a contribution in hydrological and agricultural drought interaction knowledge by developing multivariate L-moments between soil moisture and low flows for northeastern U.S. streams.

Recently, Professor Eslamian has completed the editorship of eight handbooks published by Taylor & Francis (CRC Press): the three-volume *Handbook of Engineering Hydrology* in 2014, *Urban Water Reuse Handbook* in 2015, *Underground Aqueducts Handbook* (2017), the three-volume *Handbook of Drought and Water Scarcity* (2017).

Faezeh A. Eslamian is a PhD candidate of bioresource engineering and research assistant at McGill University, Montreal, Quebec, Canada. She is currently working on the fate and transport of phosphorus through subsurface drained farmlands. Dr. Eslamian completed her bachelor's and master's degrees in civil and environmental engineering from Isfahan University of Technology, Iran, where she evaluated natural and low-cost absorbents for the removal of pollutants such as textile dyes and heavy metals. Furthermore, she has conducted research on the worldwide water quality standards, wastewater reuse, and drought guidelines.

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Drought Management: Initiatives and Objectives

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Abstract There are many drought management approaches being used around the world in relation to drought response. Traditionally, responses to drought throughout the world have been reactive ones. However, monitoring and identifying the gap between securing water for food production and managing the demand and reducing risk associated with drought are crucial, and thus, an early warning system needs to be in place to respond and manage drought effectively. This chapter aims to identify some of the drought management initiatives in line with a drought policy, including drought relief programs, water trade, and effective water capture and storage. With a better understanding of the various drought management options available, a better sense of how drought is being managed can be realized.

1.1 Introduction

Drought is a regional phenomenon with characteristics differing from one climate regime to another. Significant changes in weather patterns from normal conditions commonly produce consequential changes in the natural environment with associated social and economic impacts on affected regions [12,22,44,66]. The early 1990s saw the scientific and policy viewpoints on drought as a natural disaster change to one accepting it as a natural cycle. Meteorological drought is a natural event that results from several causes that are specific to a given region [42,69]. A definition of drought based on standardized precipitation has been suggested [40]; it is the difference in precipitation from the historical mean for a specified time period divided by the historical standard deviation. As common as drought occurrences are around the world, a standard definition of drought is not recognized. Even among the experts who study droughts, a single standard definition is not easy to agree upon. In the simplest of meanings, drought can be identified as a deficit in precipitation from an expected average over an established time frame.

To better define drought, one needs to establish the context in which the phenomenon and its associated impacts are being described. Four main classes of drought are commonly recognized, reflecting the different aspects and parameters being considered:

- *Meteorological* (*climatological*) *drought* is defined as a deviation from normal precipitation conditions over a period of time [23].
- *Agricultural drought* refers to a lack of adequate soil moisture for crops or pasture.
- *Hydrological drought* reflects reduced precipitation for an extended period, leading to deficient water resources [72]. It is the deviation of available surface and subsurface water from average conditions.
- *Socioeconomic drought* recognizes the relationship between supply and demand for water, such as when low water supplies negatively affect communities in terms of businesses (economies reliant on crop yield and livestock management) and social behavior.

As their names imply, these diverse drought types impact different sectors, but in most instances, the impacts related to each type overlap both temporally and spatially. All droughts begin with a deficiency of precipitation over some time frame. These early stages of accumulating precipitation deficiencies are commonly referred to as meteorological drought [60]. A continuation of these dry conditions over a longer period of time, sometimes in association with above-normal temperatures, high winds, and low relative humidity, quickly results in impacts on the agricultural and hydrological sectors. Meteorological droughts are driven by a change in the local meteorological conditions. The geography and climatology of a region play an important role in what defines meteorological drought since regions have very different precipitation regimes. Meteorological droughts can develop quickly, but they can also end just as quickly if the precipitation deficits are relatively small. However, these drought may also linger on to become a multiseasonal event and develop into one of the other types of drought. The identification of the beginning or end of drought conditions is debatable. Low rainfall in itself does not constitute the commencement of drought, and rain or flooding over prolonged periods of drought does not necessarily signal the end of drought either [62]. Water scarcity refers to a shortage in the drinking water supply, whereas drought refers to the lack of water for rainfed crops, irrigated crops (mainly food crops), and also for the environment, resulting in desertification. The poorest section of population is affected most. Villagers who keep the watersheds well managed with soil and water conservation practices, forestation, and the augmentation of recharge to groundwater do not suffer from water scarcity [6]. Unfortunately, desertification, land degradation, and drought are contributing to the global water crisis. As a consequence of desertification, land degradation, and drought, falling water tables are widespread, resulting in serious water shortages and salt intrusion in coastal areas.

The exacerbation of desertification in Africa and the extended droughts experienced by the continent have gone unrecognized on many fronts and have been identified as having implications for the implementation of the Millennium Development Goals. The UNCCD is working to address drought monitoring, preparedness, mitigation, land degradation, and desertification. It has been widely reported in the Middle East, Africa, Latin America, and Asia that drought causes desertification, falling water tables, and pollution, forcing communities to abandon their villages and migrate [7]. Drought as an environmental condition affects a wider geographical area than most other natural disasters. In 1991–1992, sub-Saharan Africa experienced drought in a region of 6.7 million km^2, affecting 110 million people [69]. Similarly, Fishman [22] highlighted the various water scarcity issues in India, Las Vegas, and the Murray-Darling river basin in Australia, including recycling wastewater for potable uses. With the growing population and increasing impacts of land management practices, the situation is expected to worsen in the future, especially in areas more vulnerable to climate change [29,37]. In areas of low economic development, drought has considerable impacts on local populations and ecosystems [36], exacerbating the negative effects on agricultural activities and precipitation deficiency and culminating in socioeconomic drought impacts such as the degradation of land and other problems with sanitation, health and hygiene, high infant mortality, and low immunity in children.

The most severe social consequences of droughts are found in arid or semiarid regions where the availability of water is already low under normal conditions. Droughts should not be confused either with aridity, which is a permanent feature of a dry climate, or with water scarcity [6], which implies a long-term imbalance between available water resources and demand. Drought research and operational applications have been lagging behind infrastructural in flood-prone areas. There is both an urgent need to address emerging issues in drought research and management and to interact with the scientific and operational communities, as well as policy-makers and the general public, to raise awareness of potential drought hazards. This chapter gives a brief account of the management approaches adopted in drought, including during drought relief activities, but also toward drought proofing.

1.2 Drought Monitoring

The key to understanding drought is to grasp its natural and social dimensions, with the goal of drought risk management to focus on society's coping capacity, resilience, and effective management of drought assistance [46]. The management of drought takes a risk-based approach in analyzing and adapting to conditions [49]. In order to effectively manage the risks to water resources and food security via drought adaptation and sustainable farming practices, a reliable method for monitoring and prediction of drought is required. Several agencies provide drought monitoring and prediction services around the world, such as the Global Water Partnership's Integrated Drought Management Framework, the U.S. Drought Monitor, and the Experimental African Drought Monitor [34,64]. In keeping with the different characteristics that are perceived as drought, these services employ different assessment techniques and indices in providing early warnings. Drought monitoring focuses mainly on observed data and trends using various techniques [39,54]. Drought prediction refers to both an estimate of what might happen over a specified time period and a degree of certainty about the likelihood and precision of the estimate. Drought monitoring tasks include the surface water monitoring, catchment management practices, groundwater monitoring, river management, and assessment of the actual environmental water demand and, potentially, the multiple forms of water consumption [26,74]. These employ different assessment techniques and indices in providing early warning. Drought monitoring generally can inform broader policy development for water management and has been an important planning instrument [4,27,52,55]. Primary producers, insurance companies, and importers and exporters may benefit from the provision of drought information at seasonal and subseasonal time scales. On a decadal and multidecadal scale, the government and large organizations would use such information for policy development, infrastructure, and regional development programs. Drought monitoring and prediction are also useful for resource planning, decision-making, infrastructure planning, fire risk management, and conservation of biodiversity [47,53,55]. The basis of human sustenance, agricultural production, is closely linked with the availability of water and actual crop evapotranspiration, which can be monitored by the water balance during the crop-growing cycle. Advances in remote sensing and satellite technology have helped in monitoring crop water use and production. A drought index [34,59], which assists in the analysis of temporal and spatial variations in vegetation and crop water use, has long been recognized as an important tool in drought monitoring.

Drought impact monitoring is required to identify interactions between natural characteristics of meteorological drought and human activities that depend on precipitation to meet societal and environmental demands and to determine appropriate drought management responses [32,42,69]. Drought has long been recognized to be increasing in frequency, so monitoring and warning services and the dissemination of meaningful warnings to the general public thus require a comprehensive and integrated approach to a collaborative process and a review of the best-available evidences and predictions. As drought is ultimately measured in terms of its impact and not just rainfall deficiency, no single index is sufficient to measure the impact of drought on a particular sector or application. The purpose of a drought monitoring index is to coordinate and facilitate the development, assessment, and application of drought risk management tools and policies with the goal of improving drought preparedness and reducing drought impacts [63,65]. Therefore, most such indices will focus on monitoring and assessing drought and assessing risks and vulnerability connected to drought.

Drought has been and will continue to have some of the greatest impacts of climate and hence demands the development of a common framework and new drought-related climate services [60,66] and multiyear drought predictions and projections [46]. Drought monitoring relies on the analysis of trends using various techniques based on the observed surface water data [14,51,53,76–78,80] and groundwater data [73–75]. Drought prediction refers to both an estimate of what might happen over a specified time period [24,25] and a degree of certainty about the likelihood and precision of the estimate. Moreover, the model can be used to generate maps showing the runoff variation over the basin with the particular chance of occurrence in the future [1,50,58]. Results indicate that the statistical method is a useful procedure in probabilistic forecast of future droughts, given the fact that spatiotemporal characteristics of droughts in the past are suitable for probabilistic drought forecasting [5,11] and have the potential to improve drought characterization in different applications [21,23,38].

1.3 Drought Management

Socioeconomic definitions of drought associate the supply and demand of some economic good with elements of meteorological, agricultural, and hydrological drought. It differs from the aforementioned types of drought because its occurrence depends on the time and space processes of supply and demand to identify or classify droughts [17,22,27,61,66,67,83]. Drought monitoring and prediction involve the integration of complex series of information, including soil moisture, rainfall, socioeconomic, and industrial conditions, and the service should be comprehensive to cater for the wide range of user groups [35,41,58]. The drought severity index and remote sensing information have limitations as the soil type and soil moisture data used would be more relevant to irrigation needs. Indicators based on inflows to water storages and catchment runoffs to unregulated rivers are required. Indices that take into account the time scale and spatial scale of a drought are important, and these are best developed through international cooperation. Users also require drought predictability with adequate fine-scale resolution and accuracy for application at a local scale. Geographical information system (GIS) and climate modeling are very useful in terms of historical and future events. There is a need to improve seasonal forecasting, considering the variability in climate [67,74,81,82]. A 6- to 12-month outlook is noted to be highly desirable. Confidence in data is very important as farmers and livestock managers need realistic information in the short and long term to manage various aspects of their business. Such confidence will also serve in planning water storage operations for the water supply needs of farmers and livestock managers and also assist in policy and planning at the water authority level. The implications of drought are expected to have a number of important biophysical impacts [16,36], which could potentially have a significant impact on drought mitigation. These include impacts on the following:

- Climate and water supply
- Vegetation and soil
- Agriculture and forestry
- Human comfort health and disease patterns
- Ecosystem (groundwater dependent and springs will dry up)

These impacts could potentially create social and economic problems in relation to the flooding of roads, infrastructure capacity, water supply, and human health. This may have particular relevance to the way policy-makers manage infrastructure (say coastal/harbor facilities), conduct training operations, or manage water supply in drier areas. Management tools to address drought could include

- Identification of key issues
- Hazard assessment
- Risk characterization
- Preparation of adaptation responses

Droughts have been long seen as a manifestation of scarcity of water due to untimely and inadequate rainfall. This is further intensified due to human interventions, often on an unsustainable basis. Although droughts are not a new phenomenon and people in certain parts of India have been coping with drought on a regular basis, it is certainly not a happy scenario to be in. The effects of drought are felt by almost everyone, though differently and with a time lag depending upon a complex set of factors that are linked to so-called development indicators. The impact is most felt in rural areas with the poor and those living directly off natural resources (such as land and water) bearing the brunt. Similarly, drought is felt less in urban areas, where the means to basic necessities is available in higher quantity. The efforts of the administration to address the drinking water crisis in urban areas by having piped water supply schemes installed at a huge cost and sourcing water from long distances from the countryside prove the point. By such efforts, the problem is only enhanced or transferred and seldom mitigated, the key reason being that the resource management is skewed toward supply side. A recent review of the common pool resource management has thrown up the near absence of demand-side management of groundwater that explains the ever-depleting water levels and unsustainability, in spite of the widespread watershed development programs promoted by the government, wherein demand-side management forms an important integral component [4,48].

1.3.1 Identification of Key Issues

Monitoring and identifying the gap between securing water for food production and managing the demand and reducing the risk associated with drought are crucial. The current drought prediction services need to be compared with drought-specialized early warning services, and gaps in information available need to be identified. Data collection includes a search for literature and interviews of key stakeholders. The respondent organizations provide detailed information that will provide considerable insight into drought monitoring and prediction activities in their relevant jurisdictions. Combined responses indicate that the requirements and current practices vary widely among nations. Some organizations or state jurisdictions have developed drought monitoring and prediction services to cater to local situations and needs. International organizations were seen to share information based on requirements. The specific requirements of individual states/provinces and agencies in a country resulted in little duplication of effort in addressing the needs.

A country's landscape is unique in terms of land management differences, precipitation variability and rainfall patterns, soil type variability, geography, and population distribution. Therefore, data from overseas need to be tailored to specific situations and some solutions would not be practical at all. The indices used in drought monitoring and prediction by international agencies offer some technical challenges across varying land management and precipitation patterns. Studies have shown that a country requires multiple indices, given the diversity of environments and farming systems. There is also a perception that indices tend to smooth rainfall data while masking extremes.

Currently, there are some gaps in the information available on drought in terms of monitoring and prediction. The use of GIS and climate modeling with a time domain is valuable in terms of historical and future events. There is a need to improve seasonal forecasting, considering the variability in climate and how the information is used locally. Confidence in data at all time scales is required to inform operational decisions in the agricultural sector in the short term and to guide the development of business risk profiles in the longer term. Such confidence would also serve in planning water storage operations for water supply. Multiple drought-monitoring indices are available to describe the different dimensions of drought and trends over time [56,59,70]. However, these indices are not used consistently for monitoring and reporting [2,3,15,22,27,58]. While drought monitoring services are used in many nations, existing drought forecasting and prediction services are limited. A potential user of drought prediction services plays a key role in providing rainfall forecasts and information on temperature and evapotranspiration over the country to allow local agencies to convert them to indices useable within their area of operation. For practical purposes, users prefer segmented forecasts into short-term (up to 21 days), medium-term (up to 6 months), and long-term (years) projections to achieve a comprehensive and accurate service [60].

The conventional focus of meteorological services to present information in the form of spatial weather maps may contribute to a continued focus on spatial technologies. Focus on spatial information is likely to grow as spatial technologies, remote sensing, and modeling capabilities continue to develop.

However, a balance is required to ensure that improvements in spatial technology do not constrain the development of improved predictive methods for temporal forecasts.

Seasonal drought forecasting is presented within a multivariate probabilistic framework. The standardized stream flow index is used to characterize hydrological droughts with different severities across the river basin. Since stream flow and, subsequently, hydrological droughts are autocorrelated variables in time, a multivariate probabilistic approach is used to perform drought forecasting within a Bayesian framework, and this probabilistic forecast model can provide insights to water resources managers and stakeholders to facilitate the decision-making and developing of drought mitigation plans [38,43,79].

Previous studies did not address the fundamental issue of social acceptance of climate data. Members of the public frequently comment on perceived inaccuracies in short-term weather forecasts. Droughts should not be confused either with aridity, however, which is a permanent feature of a dry climate, or with water scarcity [6], which implies a long-term imbalance between available water resources and demand. Public debate over the existence and causes of climate change continues. Given the level of skepticism in climate projections in some sectors, it is suggested that drought monitoring and prediction services have two primary purposes: to guide informed risk assessment and decision-making by the government, the private sector, and individuals and to educate the wider community and communicate climate information. Management initiatives need to be tailored to specific situations and some solutions would not be practical at all. Due to the differences, the indices used in drought monitoring and prediction by international agencies offer some technical challenges. Drought monitoring and prediction involves the integration of complex series of information. In the past, drought was mainly reported in terms of rainfall and mapping of other information. Long-term forecasting has been identified as an area for improvement. Existing long-term predictions provide a level of confidence in climate scenarios. Social acceptance of climate data is a key point to be considered.

Boundaries often seem slightly blurred in relation to drought. The FAO conducted an excellent study on the impacts of droughts and mitigation measures in the Limpopo River Basin (Southern Africa). A point strongly emphasized in this study is that a drought is seldom defined merely in terms of an event and should rather be defined in terms of the likely impacts that will result from an existing condition (reduced groundwater recharge, falling water tables levels, etc.). Meanwhile, the underlying condition that manifests as a drought may not be directly linked to a temporal climatic variation but is likely to be influenced by water resources management practices and land use. When we do not have rain, we have no water to produce for drinking. When it is raining, we have too much water and are in danger of flooding. Also, it is suggested to look at some of the rules and regulations of the water management district governing water use for public water supply, irrigation, and industrial process. Deeper aquifers (e.g., the Floridan aquifer, the United States) are brackish to salty enough to require high-pressure reverse osmosis treatment. Florida's water history has been a struggle between the coastal urban areas and the internal environmental areas over water supply.

The lack of soil moisture data is seen as a major limitation as remote sensing currently provides limited information on moisture at the soil surface. Information on soil moisture at greater depths is required for the monitoring and prediction of agricultural droughts. There is a need to integrate climate data with agricultural and hydrological models to provide better information to monitor and predict drought conditions. Longer-term forecasting has been identified as an area for improvement. The maximum time frame for prediction based on current capability is reported as 6 months, because of the predictability of El Niño–La Niña behavior, and there is a severe lack of peer-reviewed and validated capabilities for short-term forecasting and longer-term projections. Existing longer-term projections provide a level of confidence in climate scenarios, but these are of limited use in describing the severity and duration of individual events. There are more dimensions and difficulty in drought prediction than there are in flood prediction, and therefore, currently available flood prediction methods may provide one option to be expanded and refined to meet the quantitative and probabilistic requirements for drought information. Longer-term drought assessments are also complicated by the so-far limited understanding of the interactions between the drivers of El Niño and La Niña events and other long-term climate features, such as the Indian Ocean dipole [52,57].

1.3.2 Hazard Assessment and Environmental Management

A summary of topics related to hazard assessment and environmental management are highlighted as follows:

- Management of an individual site's future need to manage floods to build resilience.
- Putting water back to wetlands should be included in management arrangements, as well as shutting down wetlands (closing regulators) in pursuit of different outcomes for different wetlands. With this type of policy in place, it would be okay to shut wetlands off during drought as a measure to save water, but this is often subject to argument whether it will become the practice. The shutting down of wetlands still needs to be monitored, for example, to control the mosquito population. It remains unclear as to whether there has been permanent environmental damage caused (including that to wetlands) by drought. There is a risk that wetlands are now perceived as a water waster because of their closure during the drought at the expense of the availability of water for human needs.
- Which process decided that the environment did not get any water?
- We describe critical human needs but where are the "environmental needs"?
- Consistent criteria and agreed triggers in advance so that we can have options at the ready.
- Wetland allocations differ during drought and other conditions.
- "No species lost during drought! Is this correct?"
- Timing of water delivery is crucial to the population growth/maintenance of some species.
- Environmental regulators.
- With recovery through increasing flows, it is important to study the outcomes.
- Freshwater needed in lakes.
- Management choices to be made for the communities concerned.
- Toxins from flood plains ending up in rivers.
- Crises over funds for the monitoring of toxins in the water.
- There is so much information and stories need to be told. In times of crises, the community needs to be kept informed.
- Farmers need to know who to contact in times of crisis.
- The need for an acid sulfate program to learn management techniques from farmers, such as contouring to revegetate.
- Resources are required for monitoring.
- Water-critical areas and environment needs.
- Clarify the decision-making process.
- What culture currently exists around the community and the environment and how do we change/improve?
- Landholder experiences around lower lakes should be documented.
- Drought and flood management to build resilience.
- Wetlands were perceived as a waste of water by the community.
- The dry phase of wetlands was of no benefit.
- It is unclear whether there are examples of irreversible damage.
- Ongoing monitoring will tell if there is any permanent damage.
- Who provides funding for monitoring during crises?
- Ongoing research needs to learn from drought impacts.
- The next drought should not be as extreme.
- We have never extracted as much water out of this system as we did during this drought.
- Reserves need to be stored.
- Government structures for responding to drought are very different.
- Some natural funded management groups are better resourced than others, and the ability to invest on the ground is very different among different nations.

- Some species may not be recognized; that is, there may be an absence of pre-existing literature on some species found in the postdrought assessment.
- The ability to plan for drought during nondrought periods is essential and just responding to drought is not enough.
- Linkages between the government and natural resources management groups are important and need to be acknowledged.
- Better integration is needed between departments/states and work out who owns the responsibility for what in the environment departments.
- Contingency plans for different areas of drought and how they relate to each other.
- The limitations in responding to a major natural resource threat such as drought and planning for the next drought.
- Significant resources are required for sufficient monitoring to occur and data should be accessible.
- The decision-making process for managing environmental water needs to be clarified for environmental managers.
- It is uncertain as to whether the Basin Plan will address some of the environmental risks experienced during drought.
- There is a need to plan for drought during nondrought periods.

1.3.2.1 Drought Impacts

Droughts are now considered as a process, not a phenomenon, and droughts have severe impacts on many events, societies, economies, agriculture, and ecosystems. They are complex systems, with impacts dependent on meteorological, hydrological, and land surface factors as well as on water demand and management [9,40]. However, in addition to looking at the back-end "impacts", we should also consider the front-end "causative factors," which are contributed, in a large measure, by humankind, and exacerbate the inhomogeneities inherent in the hydrological cycle [61,64]. These factors convert weak, infrequent disaster events such as droughts into more frequent and stronger episodes. There may be many other events that are attributable to our "human" actions. People tend to believe that all these events are no more discreet but continuous, and these events together are now recognized as climate change [12,17,22,29].

Drought is a natural hazard caused by large-scale climatic variability and thus cannot be prevented by local water management. Water scarcity refers to the long-term unsustainable use of water resources, which water managers can influence [42]. Making the distinction between drought and water scarcity is not trivial, because they often occur simultaneously. An observation-modeling framework is considered as a preferred choice to separate natural (drought) and human (water scarcity) effects on the hydrological system, and the basis of the framework is the simulation of the situation that would have occurred without human influence, the naturalized situation, using a hydrological model. The resulting time series of naturalized state variables and fluxes are then compared with observed time series. As a second, more important and novel step, anomalies (i.e., deviations from a threshold) are determined from both time series and compared. Application of the model shows that the impact of groundwater abstraction on the hydrological system is, on average, four times as high as the impact of drought. Water scarcity resulted in the disappearance of the winter high-flow period, even in relatively wet years, and a nonlinear response of groundwater. The observation-modeling framework helps water managers in water-stressed regions to quantify the relative impact of drought and water scarcity on a transient basis and, consequently, to make decisions regarding adapting to drought and combating water scarcity [33,67,71,72,79].

The past decade saw large areas of the world subjected to the worst drought conditions in living memory. This drought has come to be known as the Millennium Drought and is widely regarded as having had a greater impact on communities and the environment than other long-term droughts [8,20,30,83]. In most areas, reduced rainfall created challenging conditions for dryland farmers and reduced runoff to major water storages. In addition, there was low rainfall and runoff in important catchments in the headwaters, resulting in the worst inflows to storages on record. The effects included the following:

1. Most river flows were drastically reduced.
2. Allocations to irrigators were well below historical levels, creating economic hardship for irrigation-dependent communities.
3. Water levels fell in many places.
4. The environment became severely stressed from an extended period of low flow and a lack of floodwaters to rejuvenate floodplains and wetlands.

There are seven billion people to feed on the planet today and another two billion are expected by 2050. It is estimated that every person consumes between 2 and 4 L of water per day. Most of the water that people consume is embedded in the food they eat. For example, producing 1 kg of beef requires 15,000 L of water, while producing 1 kg of wheat requires 1,500 L. As populations increase, especially in dryland areas, more and more people are becoming dependent on freshwater supplies in the land that are becoming degraded. This is not sustainable. Water security, like food security, is becoming a major national and regional priority in many areas of the world. The implementation of the United Nations Convention to Combat Desertification (UNCCD) has a significant role in the sustainable availability of clean, adequate, and safe water for human consumption and economic development.

1.3.3 Infrastructure and Risk Characterization

The complexity of drought over different time scales, geographical regions, and dimensions for different users has resulted in the development of regionally focused information services within Australia, separately, by various agencies [20,28].

Under natural conditions, river flows would produce regular floods, which would flush the system and provide water to floodplains. Most of the system is now highly regulated with many structures such as that have altered the natural pattern of flows. After almost a decade of drought, a return to wetter conditions throughout the basin led to widespread flooding. This widespread flooding was good news for the environment and enabled many species to recover from the effects of a long drought. Despite its many benefits, the flooding caused widespread damage to property and also delayed new and ongoing work scheduled to be carried out along the river. Issues to consider are

- Business infrastructure
- Community infrastructure (e.g., tourism, education)
- Additional water storages
- Desalination—education on reliance on the amount of river water
- Ecological management
- Water savings from wetland management (wet/dry cycles)
- Selling environment allocations in the market
- Water diversion
- Evaporation
- Dredging
- Policy debate—socioeconomic models
- Flooding
- Water supply shortage

It is important to use the time before the next drought to determine the priority for spending money on infrastructure. This can be achieved through a fully costed scenario analysis. Salinity of water supply is a major threat to food production and infrastructure [55]. The natural and man-made rivers and water storages should not be allowed to drop again below a certain level because significant infrastructure issues start to arise as a result. Capacity and corporate knowledge are diminishing rapidly due to staff turnover. This subsection highlights how approaches used to deal with risks and uncertainties in all areas of socioeconomic development can positively or negatively affect water risks and uncertainties, leading to potential restrictions or an increase in the management choices available to water managers. Risk management, whether in the form of avoidance, reduction, or mitigation, is integral part of all policy-making. Moreover, the complexity of the risks and uncertainties now facing society is increasing and accelerating. Understanding the way choices impact water can help shape decisions that maximize benefits in all domains, creating safer and more sustainable pathways for long-term development. This also requires a clear-minded consideration of immediate, medium-term, and long-term trade-offs [71].

1.3.3.1 Learning from Extreme Events

The role of science in responding to drought is to inform policy and management. But to protect ecosystems, given competing demands and uncertainty about future climate, requires robust science (including economic and social science) to inform the debate on water use and identifies the need for a predictive capacity regarding climate, hydrology, hydrodynamics, water quality, and ecological response [22,23]. The realities of drought are that active storage levels are very low and flow is well below average; water levels fall; and the salinity of water bodies including wetlands, which support irrigated agriculture, tourism, and fisheries and provide refuge for aquatic birds, rises. The ecological impacts of increasing salinity during drought became evident with the decrease in the numbers of invertebrate taxa associated with increasing salinities. Experience from drought has indicated that a target salinity threshold should be set and that high flow alone has not flushed out the built up salt in the system. The degradation of water quality during a drought suggests that

- New policies are needed to provide adequate flow to maintain the river flow.
- Mismanaging the past leads to overmanaging the future.
- Running our ecosystems down leaves them vulnerable to further change.
- There is an imperative to conserve now so that ecosystems will be resilient and able to cope with extremes climate in the future.
- A new investment in new science for tomorrow's challenges is vital because we cannot just assume that mining historical data will give us the answers we need.

The experience has provided several key learnings. By and large, a majority of people have self-respect and would like to be paid appropriately for their work. Our initial apprehension that people may not turn up for drought work was belied when we saw that the entire village(s) reported for work. Within two weeks, a majority of those who migrated also returned and resumed the work (except those who committed to share cropping elsewhere). This indicates that people do not willingly migrate but do so on compulsion. They have also decided upon appropriate rates for different soil conditions and proved that they are good decision-makers. That a properly planned and implemented strategy would also address equity and gender issues most satisfactorily is proved by this approach. Thinking and installing systems is very essential for both efficient implementation and transparency. Procedures need to be developed for all activities as part of the control and monitoring mechanism that helped avoid confusion and duplicity, while increasing transparency. The systems that were established and the procedures devised have helped in proper accounting, whose significance was highlighted at the time of auditing by the donor agencies. It is pertinent to mention how a village-level institution has resolved a potential conflict all by itself.

1.4 Response to Drought: Drought Management Initiatives

Humans survive change via adaptation. Strengthening the adaptive capacity of populations at all levels is among the most important challenges facing development and human society in the broad context, encompassing climate change and other change processes, among other things, and the critical importance of transboundary flows of information, funds, goods, services, ideas, and often people in determining the adaptive capacity of local populations. The ability to adapt to local problems such as floods and droughts often depends on systems and flows that connect to the regional and global levels. More specifically, understanding this and addressing its inherent implications for trade, migration, and other sensitive global policy arenas are among the most significant challenges facing society in the coming century. Adaptive strategies are the result of collaboration that attempts to understand and disaggregate the factors that enable communities to adapt to floods, droughts, and climatic variability by examining the courses of action households actually take during these events and by gathering the insights generated in a wider review of regional trends, government programs, and systems theory. Although focused on floods and droughts, many of the insights generated through research, including factors that heavily influence vulnerability and adaptive capacity, have potential relevance for other situations where livelihood systems are disrupted and adaptation is essential [45]. This section provides a summary of the information and opinions shared to document and establish the key learnings from government responses to drought as part of drought management initiatives. There are also additional learnings that can be garnered from considering the basin-wide response to the Murray–Darling basin drought, which may warrant the future involvement of other jurisdictions [13].

1.4.1 Drought Policy

Policy responses that concentrated on food needs, on access, and entitlements to food [7,9,19,68] too have made impressive figures of food production at the macroeconomic (national) level but did not make much difference to the communities, owing to a host of distribution-related issues and more importantly, due to the lack of sustainability of such an approach. People recognize the value of water, especially the farmers in agricultural regions of India. Ensuring some sort of "empowerment" where people take water management decisions will alone address drought. One of the main requirements for people to remain in their villages and often the first problem faced is not access to food, but rather the availability of water [13]. In securing water for domestic or industrial uses, it is important to

- Generate and document innovations and lessons learned.
- Offer incentives to researchers and water managers, from policy to implementation.
- Build the evidence base to inform policy development and implementation.

Review of the drought is considered important because

- The recent drought resulted in one of the largest ever collection of government responses to a natural resource management event in history, making it a significant living laboratory.
- It provided an opportunity to review an adaptive management approach on a large scale, recognizing that the lessons learned would be particularly valuable given future predictions of increased frequency and severity of drought due to climate change.
- The response to the drought is of significant international interest and the workshop provided an opportunity to better understand common learnings from across government and research communities and to communicate the messages more widely. The goals of this chapter are therefore to
    - Identify common learnings from across organizations and determine the keys to successful collaboration in responding to drought.
    - Determine effective means for the government to engage with the community during periods of high, collective community stress.
    - Identify outstandingly high priorities for new research and/or policy to help respond to drought or equivalent natural resource stresses in the future.
    - Record the lessons learned that may be of interest to other public administrators and researchers to consider issues regarding the decision-making process and the collective government response that was put in place to direct government actions and facilitate in the initiation of discussions on four themes (legislative change, policy, and community engagement; the role of science; environmental management; and risk and infrastructure management).

Water resources management and other water-related decisions and policies are frequently guided by economic dimensions [18]. Economic considerations, including efficiency, equity, production, allocation, and pollution, have expanded as water resources have become scarcer both in terms of quantity and quality. While economic analyses applied to the water sector are useful and educational, their policy implications are less obvious for guiding policy-makers. *Water Economics and Policy* will address the economics–policy interaction by publishing highly technical water economics research with clear relevance for policy. *Water Economics and Policy* will aim to target a wide range of economic questions at the local, regional, national, and international levels. It will accommodate work that is focused on specific sectors (such as the urban, hydropower, irrigation, and environmental sectors) as well as work that is inter-sectoral in nature. Science provides knowledge that can act as a guide for management. While science contains uncertainty this should not be a reason to marginalize it in the decision-making process. Instead, the uncertainty needs to be noted as is the case for other information types (e.g., financial, social). Science interpretation is critical to political decisions and there is a need for scientists to become more proactive in communicating the results of their work. Scientists need to invest in building trust with decision-makers and the community. There is a need to systematically decide what is required of science and how to get the most out of it. Lessons can be learned from the management of the recent drought in a river/catchment basin that demonstrate the value of taking a truly adaptive approach to scientific investigations to support management and not waiting until a crisis occurs. This is further demonstrated by the operation and management of drainage infrastructure in some countries.

As drought conditions worsened, the department in charge of disaster management instructs to

- Coordinate a series of government responses
- Deliver evidence-based and innovative support
- Be responsive to regional needs and be consistent with national exceptional circumstances policy and programs

This leads to the adoption of a step-by-step and adaptive approach, progressing through phases from crisis to recovery to preparedness, with cross-agency action and collaboration providing ready access to services and support. Holistic support is provided by combining farm business support, family and community support, and employment and workforce support. As a result of this support, a number of corridor programs and actions can be initiated, including

- Interest rate subsidies
- Relief payments
- Exit grants
- Professional advice and planning grants
- Irrigation management grants
- Financial counseling
- Health and well-being counseling and support
- Alternative employment assistance
- Critical water allocations
- Information and decision support

These programs and actions supported the potential for rural communities to recover and build regional capacity. The programs were regarded as successful as they helped to mitigate impacts on the state's agricultural food production, economy, the fabric of rural communities and environment, and landscape.

1.4.1.1 Legislative Change, Policy, and Community Engagement

The importance of community engagement in informing policy was reenforced. Focused community engagement should be done at the same time as developing communications material. Community engagement became a positive mechanism during the drought for conveying information about how the state was responding and provided an opportunity to inform policy development. Each region is different and requires a tailored community engagement approach. A few experiences and lessons among those are as follows:

- A collective of government response emerged. Drought preparedness planning: building institutional capacity and Adaptation Policy.
- Rapid feeding of information back through networks.
- It is important to make sound, well-informed decisions with minimal negative consequences. To not make a decision has more potential to lead to even more problems.
- How do you pass the knowledge on? There is a need to document decisions and processes.
- Decisions were more bipartisan than normal. How do you engage both sides of politics in a bipartisan way?
- Enough time is needed to help people take a lead in the community.
- It is needed to ensure there was an informed debate, one based on information on what is happening elsewhere.
- It is needed to work out how to inform all relevant groups affected.
- It is difficult to run a consultation process that makes the information transfer stick.
- Each region is different and needs a case-by-case engagement process.
- There is a need to draw on the knowledge of people that might have moved on from their roles/employment during the drought.
- A common venue was important for information sharing.
- Negotiated storage rights were an example of policy changes in response to the drought.
- There is a need for consistency of information and clarity on decision-making processes.
- One of the key successes was the distribution of information, especially frequency of information distribution.
- We did not communicate the severity of the problem as much as we could have, in part because we did not believe the severity of the problem or comprehend it.
- Do not attempt to convey information through a public meeting.
- Structured engagement through established groups.
- It is needed to preserve the social capital that emerged during the drought.
- Tight time frames often limited effective consultation.
- Most groups were spontaneous and focused on issues.
- Time and funding are needed to help continue to build social capital.
- Continue to invest in engaging community networks.
- Recognize that interest in engagement is driven by purpose.
- Invest in community organizations where people are cooperating for a purpose.
- Agencies engaged with the community in a way they would not have normally done so.
- It is needed to avoid urges to over-consult.
- It is okay to make a few mistakes.
- Invest in people and in extension.
- Ways to deal and communicate with people who do not get what they want need to be found.
- Succession planning in the community is important.
- Support people in government roles.

The recent drought was unprecedented in terms of magnitude and duration. The significant low flow event was met with an expectation that drought would soon finish, yet there followed successive years of low flows in the Murray as well as low inflows. As a result, the quality of the state's metropolitan water supply was at risk because of salinity and acid sulfate soil issues emerging. It is not an exaggeration to say that countries were facing a catastrophe and, hence, a host of government responses was required. This led to the establishment of the Water Security Taskforce and Water Security Technical Group, whose immediate goals were to maintain water for critical human needs as well as to provide a share of water for the needs of the environment and agriculture communities. Specific actions in response to the drought included

- Modification and lowering of major pumping offtakes for water supply
- Pumping water into storages to provide a buffer against potential water quality issues
- Securing a water reserve each year to provide for critical human needs
- Building additional water reserves through market purchase
- Construction of irrigation and stock and domestic pipelines around water bodies
- Assistance provided to the agriculture industry by purchasing water to keep permanent plantings alive
- The temporary closing of permanent wetlands to save evaporative water losses and prevent high-salinity and nutrient-rich water from draining back into the river
- Negotiations undertaken through agreements for disconnection of wetlands and required dredging processes
- Fast tracking of the country's water quality improvement program
- Fast tracking of environmental approvals for dredging to enable navigation and dredging
- Extending footings on ferries to allow them to operate at lower river heights
- Monitoring for salinity, acid sulfate soils, and riverine ecology
- Investigations into levee bank cracking
- Development of a State Water Security Plan and investigations into the harvesting, treatment, and use of storm water
- Encouraging water conservation through restrictions rebates on low flow devices and rainwater tanks

The involvement of a local NGO with credibility will go a long way in mobilizing the people and ensuring transparency and the success of the drought program. This is because local NGOs generally would have developed a good rapport with the communities. A drought proofing committee should be formed in drought-prone areas in order to ensure that government schemes are properly planned and implemented to strengthen livelihoods and develop resilience. This committee should ideally be composed of the district collector, relevant government and department heads, and local leading NGOs. In times of drought, this committee will identify villages affected, prioritize activities at a broader level, and recommend the release of funds. It will also monitor and evaluate the programs and submit reports to the state government. Village-level committees should be given the responsibility of deciding the activities and implementing them [49].

Overall, the Drought Response Program successfully achieved its goals: water for critical human needs were met, water quality was maintained at a level suitable for drinking, acid sulfate soils were managed and the entire water bodies did not acidify, no native or aquatic species were lost, the horticulture industry was assisted with purchased water, enabling it to survive, and riverbank collapse was managed as a state hazard. While goals were achieved, legacy issues remain: water quality issues persist in the water bodies and cracked levee banks persist. Scientific advice suggests that the recent drought provided a glimpse of the future under climate change, whereby droughts like this will become more frequent and more intense. Lessons learned from workshops will help put the government in a better position for the next drought and inform a united government response to the Basin Plan and address the problems of over-allocation. In this chapter, the response to drought is focused on adaptation without much detail on mitigation to climate change, including reducing emissions to reduce extremes, which are the cause for drought and stress.

1.4.1.2 Decision-Making

It is important not to forget the lessons from past drought, which in reflection provides a significant opportunity to look at what evolved as an adaptive management process. Further, it is important that we record the experience so that the next time similar circumstances arise, we can see the signs and be ready to respond sooner. A drought response strategy is expected to have the following goals:

- *Primary goal*: To maintain the supply of potable-quality water to meet the critical needs of people living in the water security zone, at all times, during the water security planning period.

- *Secondary goal*: Once the critical human needs are guaranteed for a given current year, additional river flows are to be shared between a strategic reserve for critical human needs, water supplies for the next year, the environment, irrigation, and external and domestic uses and to adjust for any surplus/deficit.

The Department of Primary Industries and Resources and the Natural Resources Management Boards were established to investigate the cause of acidification and develop management solutions. Outcomes included the Environment Protection Authority implementing a fast-tracked program of technical investigations to determine the extent and severity of acidification and to develop farm management solutions. The drought was seen as hard to manage because it was a creeping natural disaster, while floods and fires occur quickly and have a short duration and recovery can be immediately planned for, in the middle of the drought there was no knowing whether it was close to the start, middle, or end. Within the government, the triage approach provided an important way of forward planning on the basis of "what-if scenarios." The government has to weigh up issues on a daily basis with input from the Water Security Taskforce and Technical Working Group. In addition to triage planning and actions, there were a number of major initiatives, including

- Developing a carryover water policy.
- Appointing community liaison managers.
- Establishing drought response centers.
- Commencing work on the desalination plant.
- Developing the "water for good" strategy.
- Installing water filtration plants in countryside areas to ensure water quality was maintained.
- Purchasing water from upstream to meet critical human needs and protect permanent plantings.
- Providing rebate schemes to encourage people to use less water.
- Holding science forums to ensure that the best available science could be brought to bear on the environmental and water quality challenges imposed by the drought. The drought posed difficult management circumstances, as the government and agencies were on crisis watch every day.

The community engagement challenge can be tackled by setting up a number of community groups to respond to local community issues [10]. For example, working groups are established with community representatives to consider issues such as the impacts related to falling water levels, falling river heights, levee bank cracking, and access to water for pumping. The strengths of the community engagement process are that the Minister attends meetings regularly so the public had the chance to ask questions about how the government is responding directly to the Minister. The collective government response that is adopted is seen as essential. Key persons also operate as an intermediary between banks and farmers who are facing financial hardship because of drought impacts. It is recognized that this framework is necessary to prevent banks from appointing receivers or taking possession of properties of which the values would have plummeted.

1.4.1.3 Maintaining Service to Customers during the Drought

Supplies come under stress during drought and action is required to ensure supply is maintained to meet critical needs. The key issues for the water agency and its dependents are rising salinity, water quality risks, and falling water levels. A number of short-term issues arise in responding to drought, including the need to maximize water availability through water sharing with other Basin states, the purchase of temporary allocations from willing sellers interstate, and the need to make the best of what water is available through water conservation/water restrictions, dealing with limitations on major pumping stations on the river, and ensuring their continued operation. This led to pump station designs that allowed for continued operations even if water levels fell below a threshold, managing distribution system operations during restrictions and water quality issues in the river. Water sharing with other basin states focused on providing sufficient flow to keep salinity within drinkable limits and acquiring a water "reserve" that could be utilized in an emergency to meet critical human needs. The focus of water conservation is to conserve what is available for as long as possible. A drought response team is operated by the water agency and restriction levels are developed with a progressive increase in savings behind the conservation objectives. The team is responsible for issuing permits and rebate payments and coordinating community engagement and communication and operated a 24/7 call center for restriction and rebate inquiries, which peaked during the drought. Water restrictions can be applied when necessary and the result of water conservation measures was reduced consumption.

1.4.1.4 Managing Drought through Relief Intervention

The key objectives of a drought relief program are to provide the least amount of fodder required for the sustenance of cattle and to host "cash/food for work" programs (mainly through soil and moisture conservation activities). The amount collected from this distribution would be used for village development activities focused on drought mitigation [56]. Groundwater accounts significant for a portion of the irrigated area in many areas. Over drought periods, the average annual extraction of groundwater for irrigation exceeds recharge several times over, resulting in serious depletion problems throughout the district. The most common mode of extraction of groundwater is through open wells. Earlier, with high natural recharge rates, the water level in the area used to be at shallow depths. However, due to continuous overexploitation of groundwater for irrigation, the estimated net annual draft declined against an utilizable recharge. This overexploitation coupled with increased deforestation has resulted in a reduction in the natural recharge leading to a significant decrease in groundwater availability. Seasonal variations in the water level are also found to be quite large. During drought conditions, several of the wells go dry.

The drought compelled most families to reduce their vegetable intake. The consumption of green vegetables became negligible. With the average annual extraction of groundwater exceeding recharge many times over, the overdevelopment of groundwater for irrigation has resulted in widespread depletion problems throughout many regions. The water levels have been falling alarmingly every year. In response to the scarcity conditions, new bore wells can be drilled and tanker supplies can be started by the government. The prices of essential commodities such as oil, milk, and wheat can increase substantially. The crop yield is expected to reduce drastically. Due to drought conditions, local employment avenues have reduced drastically, resulting in increased migration; in most of the cases, women, children, and elderly stayed back. The key elements in project implementation included liaising with the government, discussions with the council, conducting village-level meetings, and putting in place systemic requirements. Thus, during the meetings, norms and guidelines were evolved on the entire implementation strategy. The operational principles were equity, efficiency, and sustainability, which they understood and followed during the entire effective period. Drought decreases the availability of seeds apart from upsetting the economy of the region. This makes it difficult for farmers to invest in desired inputs for agriculture.

The location of storage space needs to be identified. This space will be provided free of cost by the village. The options of various activities need to be discussed. The villagers can decide on a priority basis such as rejuvenating the existing tanks, creating new tanks, and constructing check structures (gully plugs, check dams, trenches) and plantations. Private farm bunding will be taken up as a last option and toward the close of common activities. The supervisor is responsible for monitoring and reporting the progress of planned activities as well as the future fodder, material, and cash requirements from time to time. The group leaders apprise the worker who in turn interacts with the supervisor. Maintaining systems and procedures on every transaction (in kind or cash) during the relief project is key to running an efficient and effective delivery mechanism. Apart from upsetting the economy of the region, drought also decreases seed availability. Often, farmers borrow from moneylenders and traders at a high rate of interest for meeting their crop needs. Many considered drought as an opportunity for rejuvenating local water resources along with providing employment for immediate relief. Thus, soil and moisture conservation activities such as check dams, rejuvenation/construction of water tanks, trenching, drainage line treatment, re-vegetation measures, and farm bunding were implemented. These structures, while enhancing groundwater capture, would act as a drought-proofing mechanism for future years.

1.4.2 Managing Water Demand

There was an agreement that a drought forecasting and prediction service would be of benefit to specific users [22,47]. The preference of individual agencies was to use rainfall forecasts and convert them into drought indices useable within their area of operation. Users identified a need for short-term (up to 21 days), medium-term (up to 6 months), and long-term (years) forecasts. Respondents also emphasized the need for accuracy of these forecasts. Meteorological services present information in the form of spatial weather maps. This may contribute to a continued focus on spatial technologies such as the Geographical Information System (GIS) to present drought information. It is equally important to develop an improved capacity to present temporal information. The focus on spatial information is likely to grow as spatial technologies, remote sensing, and modeling capabilities continue to develop. However, a balance is required to ensure that improvements in spatial technology do not constrain the development of improved predictive methods for temporal forecasts. Professionals agreed that there was a need to develop a national information system to streamline drought information related to exceptional circumstances by compiling national peer-reviewed data to provide drought information. A climate risk project is also run in conjunction with these efforts, supported by the development of GIS and climate modeling capabilities. Information from agencies is repackaged with internally produced data to generate seasonal drought prediction reports to assist farmers when considering overall price risk, grain logistics, and marketing. Most services do not involve any drought monitoring indices as most available indices are considered to have limited practical relevance to specific conditions, including large geographical area, a wide range of climatic conditions, low soil-retention capacity of local soils, etc. It is desirable to have drought pilot workshops to focus on the whole enterprise level, including farm planning and economic drought mitigation. This approach has been assessed as a better proactive strategy to adapt to the added variability of a changing climate than the earlier reactive, post-event methods.

1.4.2.1 Water Trade Proving a Valuable Tool for Communities

Recent water markets have allowed water to be reallocated to where the need is greatest and reduced the impact of the drought on regional production. Water trade is playing a major role in achieving the Water Initiative objective of maximizing the economic, social, and environmental values of scarce water resources. It is increasingly valued as a business tool and is now supported by the majority of irrigators. Data on the impacts of water trading on individual irrigators, industries, and regional communities are required to fulfill its obligation to monitor the impacts of interstate trade. The report confirms the main drivers of hardship in these communities, including drought, commodity prices, and exchange rates. Water trading is part of the solution in managing these difficulties. But water markets can deliver even more, and continuing reform will ensure that market structures provide greater efficiency, that participants have sufficient information to avoid uncertainty, and, most importantly, that the remaining restrictions on trade are removed. The millennium drought has had significant impacts on regional production and the proceeds from water trading sales have supported local economies and allowed many irrigators to reduce debt during that difficult time. Water purchased by the government is part of this trade and will benefit the environment. While it is true that some irrigators are leaving the industry after selling their water entitlements, others are making business decisions that rely on more opportunistic annual water allocation trading. Effective and efficient water markets will continue to be vital in minimizing the economic and social costs of managing fluctuating seasonal conditions and commodity markets, adapting to climate change, and moving to sustainable levels of extraction.

1.4.2.2 Effective Water Capture and Storage

Water harvesting is the key to drought proofing. Tanks and ponds, which formed a good source of groundwater recharge, need to be restored, developed, and regularly maintained [32,49]. Climate change studies predict that the climate is likely to become drier in the future, due to the rising concentrations of greenhouse gasses in the atmosphere. The studies indicate that the climate is likely to become even more variable, as well as drier. Therefore, in addition to more extreme droughts, there may also be more extreme floods. There is a projected impact of reduction on average surface water availability. Lack of water and a decrease in the frequency of natural flooding events are having an impact on many wetlands and other important environmental sites. The long-term health of the whole system is now at risk. With bigger drought and flood forecast under climate change, along with rapidly rising demand from growing cities and industries, managing water wisely will be central to future prosperity and sustainability.

Managed aquifer storage—the injection or infiltration of excess surface water into underground aquifers—could help secure the water supplies for an uncertain future. There is a potential to store large volumes of precious water underground to offset climate change, avoid evaporation losses, and meet national water needs into the future. There are many benefits from storing water underground; these include recharging depleted aquifers, enlarging storages without building more dams, reducing evaporative losses, reconnecting surface and ground waters, watering the landscape from underground, and creating strategic reserves in critical food-growing or urban areas. Most countries are generally positive about the idea of aquifer recharge/banking and it is widely acceptable [37]. Water that may be injected into underground aquifers include supplementary irrigation water, surplus runoff into dams, and water brought to the surface by coal seam gas extraction and other mining activities. Australia already stores the equivalent of 1800 Olympic-size swimming pools of water underground in the Burdekin region of Queensland every year and brings some up again for use in agriculture and horticulture. But in Orange County, California, they store around 300×10^6 m^3 a year—enough for household use for 2.3 million people [31]. On the face of it, managed aquifer recharge looks tremendously promising, but it needs a more detailed understanding of our aquifers, likely environmental impacts, and, of course, we need effective rules and rights for injecting and recovering water on a large scale. The scale of large floods suggests that some of this water can be used to recharge aquifers without affecting the important ecological role of floods in our river systems. Such events may be more frequent under climate change and it makes national sense to turn a problem into an opportunity. Another important reason for storing more water below ground is to protect the native landscape; this can help keep rivers and wetlands filled and ensure water is always accessible to the deep-rooted plants and acacias that are vital to our native landscapes. If a few countries manage to solve their own water scarcity problems by understanding aquifer recharge, they will position themselves as world leaders and major exporters of solutions in a world facing a growing water crisis. One of the largest untapped sources of water in Australia is the northern wet, covering the top one-third of the continent. The wish to preserve wild rivers in light of high evaporation rates makes major dam building unlikely, but potential may exist in storing some of the runoff underground [31]. Underground storage is likely to be socially more acceptable than building new dams in arid areas but it must nevertheless be carried out with care, and with a detailed understanding of the impact on other water bodies, both surface and subsurface, on natural ecosystems and communities. Artificial storage of rainwater in aquifers has a great potential to minimize water scarcity and water stress during drought situations. Hence, rainwater harvesting in normal and excess rainfall years should become an important component in watersheds and other government schemes at the district level [49].

1.5 Summary and Conclusions

In addition to looking at the backend "impacts" of the drought, it is believed to consider the front-end "causative factors" contributed in a large measure by humankind to exacerbate the inhomogeneities inherent in the hydrological cycle. These factors probably intensify disaster events, such as droughts, to become longer frequent and stronger. Many tend to believe that all these events are no more discreet but continuous and are recognized as climate change. The Millennium Drought is widely regarded as the worst on record. It impacted through unprecedented low levels of river inflows, which reduced water held in upstream storages as well as flow to the state, and coincided with extremely low rainfall. The response to this drought provides an opportunity to review an adaptive management approach on a large scale, recognizing that the lessons learned are particularly valuable given future predictions of an increased frequency and severity of drought due to climate change. Drought is of significant international interest, and that would provide an opportunity to better understand common learnings from across government and research communities and communicate the messages more widely. It is noted that nations had faced a catastrophe—if action had not been taken to respond to the impacts of the drought—acid sulfate soils would have impacted the environment of the water bodies and millions may have had to rely on bottled water and investment in irrigated horticulture would have perished. It is also noted that the drought was hard to manage because it was a creeping natural disaster unlike floods or fires because there was no knowing whether it was close to the start, middle, or end. The scale and nature of the challenge prompted a host of government responses that resulted in the establishment of a specialized government office, which led to some key features, including

1. Direct communication and engagement, which involved (a) the Minister attending meetings regularly so the public had the chance to ask questions directly, (b) the appointment of well-respected community liaison managers to work with community groups, and (c) the attendance and involvement of departmental staff in frequent community meetings and forums.
2. Evidence-based, adaptive decision-making, that while not always popular in terms of the measures that were implemented or plans developed, was essential because there was no knowing how bad the drought was going to be.
3. Major policy and on-ground achievements, such as water for food, water level, and flow regulating infrastructure interventions, and a range of bioremediation and revegetation projects around water bodies.

Overall, the Drought Response Program is assumed to have achieved its goals: water for critical human needs was made available at all times, water quality was maintained to a level suitable for drinking, acid sulfate soils were managed and entire water bodies did not acidify, the agriculture industry was assisted with purchased water enabling it to survive, and riverbank collapse was managed as a state hazard. While goals were achieved, legacy issues remain: water quality issues persist in water bodies, acid drainage from irrigation areas continues, and cracked levee banks persist.

Additional key lessons garnered include the following:

- There is a lack of awareness among the broader community, including those in the water management sector, of the large amount of quality work that was done by the public sector in responding to the drought. This work was acknowledged at the workshop by those who were not directly involved in the government's response.
- There are key ecohydrological thresholds that emerged during the drought that if exceeded will cause significant degradation.
- It is essential that the time before the next drought is used to determine the priority for infrastructure spending, using an approach such as a full costs and impacts scenario analysis that considers hydrological events beyond historical experience (drought and flood) and potential future impacts arising from climate change.
- Necessary approvals should be secured in advance with agreed triggers for implementation. The workshop can be considered as the first step of what may be a longer process to fully document and establish the key learnings from government's response to the Millennium Drought. Further work could include
  - More comprehensively documenting each of the major initiatives implemented during the drought into case studies that provide the learnings for a series of publications to be used for training and education purposes
  - Additional themes and issues such as systematically reviewing what science is required to manage regarding natural resources during drought events

- Conducting an audit to determine the ecological recovery of the wetlands drained during the drought and to develop a framework for their future management and monitoring
- Use drought learnings to inform river operating rules and interjurisdictional water resource sharing arrangements to determine whether better outcomes are possible during drought conditions

Many of the management initiatives provide detailed information that provide considerable insight into preventing drought and associated risks. Key messages from the review of drought are as follows:

- Cross-government governance structures were essential in the government being able to respond to the drought and integrated, environmental, health and safety, irrigation, drinking water, and engineering considerations.
- The impacts of the drought persist (e.g., acid drainage from the irrigation area, cracked levee banks) and communities are still rebuilding confidence, livelihoods, and the economy.
- Community engagement was as key tool in communicating the reasons why new legislation and policies were required. It could be maintained and built upon where possible to further spread the benefit of the "social capital" that emerged during the drought.
- There is a need to systematically determine and agree on what science is required to manage natural resources during such events and how to obtain the most relevant knowledge to support decision-making from the investment that is available. The recent drought demonstrates a suitable approach.
- There are key ecohydrological thresholds that emerged during the drought that if exceeded will cause significant degradation to the environment.
- It is essential that the time before the next drought is used to determine the priority for infrastructure spending, using an approach such as a full costs and impacts scenario analysis that considers hydrological events beyond historical experience (drought and flood) and potential future impacts arising from climate change.
- It is important that before the next drought, "event-ready" research and monitoring programs are prepared. This involves the design of research and monitoring based on an improved understanding of potential drought impacts informed by recent experience. This will contribute to the appropriate science being available to support decision-making processes.

The chapter is presented as being the first step in what may be a longer review and documentation process to ensure that the lessons from the drought do inform future management of such events. Next steps could include

- Further documenting each of the major initiatives implemented during the drought into a series of case studies that could in turn form the basis of an edited book, drawing on contributions from people involved with the management of the drought
- Additional work on some of the themes and issues, such as systematically reviewing what science is required to manage natural resources during drought events and identifying the need for a predictive capacity regarding climate, hydrology, hydrodynamics, water quality, and ecological response
- Determining how best to adopt an approach to adaptive management for wetlands, developed during normal rather than drought years
- Conducting an audit to determine the ecological recovery of the wetlands drained during the drought and develop a framework for their future management and monitoring
- Using outcomes from the drought to inform the development of the Basin Plan, especially with respect to setting operational targets for river height below threshold and water quality parameters
- Using drought learnings to inform river basins' operating rules and interjurisdictional water resource sharing arrangements to determine whether better outcomes are possible during drought conditions.

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2

Impacts of Drought on Social and Agricultural Systems

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Abstract Drought is a natural phenomenon that affects humanity around the globe. While the mantra of water being critical for life is widely known, people are often unaware of the fact that the vast majority of freshwater supplies are consumed in the process of food production. Modern irrigation significantly boosts harvests because it is a fail-safe measure when compared with rain-fed farming, which leaves farmers vulnerable to the vagaries of weather patterns. Climate change has made farming more unpredictable and hence distressing to farmers.

Droughts have variable effects on different parts of a country. For example, people who live in the rural periphery would feel the effects of a drought quicker than those in the urban core. This delayed effect would need to be factored into drought mitigation policies. The policies should also include early warning systems that yield relevant data from different parts of the country and the wider region. These early warning signals need to be communicated to the public in a timely manner using messages that are meaningful and comprehensible by the vast majority of the population regardless of their education level, economic class, or geographic location. Countries can bolster their drought resilience by implementing water efficiency programs, good governance, and continuous educational efforts to inform the general public about local and national water issues.

2.1 Introduction

Globally, the rate of growth in water demand is outpacing environmental capacity. This is exacerbated by droughts and extensive water pollution, which push some communities and countries closer to their political and ecological tipping points. The consequences extend beyond regional ecology, affecting political stability, triggering famines, and causing loss of human, animal, and plant life. Droughts are global environmental events that are experienced by large numbers of people around the world.

Droughts are both known and unknown phenomena. They are a known natural hazard; ordinary people recognize a drier-than-normal event when it occurs. They are unknown because they vary over time, by region, and by types of tasks people engage in. These random and occasional "aberrations in the weather" [38], therefore, require a definition that is multifaceted and layered.

A basic definition might suggest that drought refers to long periods of dryness outside the norm, but how long does an area need to experience this dryness, and to what extent, before a drought is declared? A farmer in a humid northeastern state in the United States will have a very different conceptualization of drought than a businessman in the arid United Arab Emirates. Both would agree that a drought occurs when the dryness is so far outside the norm that patterns of living, agriculture, and the economy are affected. In this chapter, we place particular focus on the impacts of drought on agriculture. One of the first areas of human life affected by drought, agriculture also affects numerous other spheres of human existence, from the economy to health and basic survival. The concept of drought is defined through an anthropocentric lens as a natural hazard that occurs when a period of extended dryness leads to economic losses, decreased crop yields, and the need for water rationing or other human adaptations to the drier-than-normal period. While constricted disciplinary lenses sometimes affect how droughts are classified [18], most researchers conceptualize them as being related to precipitation, streamflow, soil moisture, or a combination of the three. A paper by Wilhite and Glantz [68] identified the following drought categories.

2.1.1 Meteorological Drought

Meteorological drought occurs when current precipitation levels deviate from some "normal" amount over a period of time, using monthly, seasonal, or annual scales. Here, decreased precipitation is seen as a primary cause of drought, and its effects are limited to a specific region because atmospheric conditions that produce precipitation deficiencies are geographically limited.

2.1.2 Hydrological Drought

Hydrological drought refers to the effects and impacts that precipitation deficiencies (including snowfall) have on surface or subsurface water supplies. Here, it takes a longer time for water shortages to affect the wider hydrological system than in the case of meteorological and agricultural droughts. For example, while the effects of lower-than-normal precipitation may have an immediate, observable impact on crop health, it will take a much longer time to influence reservoir levels and alter power production.

The spatial scale of a hydrological drought is a watershed or river basin. When droughts occur or when available supplies become insufficient to meet the needs of the population, conflicts often arise between competing users, such as between urban and rural use, between irrigation and recreation use, hydropower production, and wildlife habitat protection. Drought events amplify the conflict and tension between different users and may spur activism by adversely affected stakeholders. In countries with weak governance and institutional structures, activism could lead to mass protests and social and political disruptions.

2.1.3 Agricultural Drought

Agricultural drought refers to soil moisture needs of a certain crop at a specific time and to how aspects of meteorological or hydrological droughts affect agricultural output. For example, water deficiency, physical and biological characteristics of a plant and of the soil, and prevailing weather conditions affect evapotranspiration levels and the overall susceptibility of a plant to drought conditions. Agricultural droughts are capable of adversely affecting the economy and reducing food supplies.

2.1.4 Socioeconomic Drought

Socioeconomic drought is what happens when demand starts to exceed available water supplies, hence impacting the activities of individuals, societies, or countries. For example, low precipitation levels can lower water levels in a reservoir, in turn reducing the generation of hydropower.

The relationship between these different types of drought and their impact is captured in a flowchart (Figure 2.1).

This chapter is focused on socioeconomic and agricultural drought and will pay heed to their interactions with human systems. As such, the predominant interest of the chapter could be classified as anthropogenic drought, a term some researchers use to describe human effects on drought phenomenon.

The researchers who study anthropogenic droughts believe that as humans impact global weather patterns and climate change occurs, the lessons learned in earlier droughts may not be applicable. Humanity, in their opinion, plays a significant role in the severity, duration, and impacts of drought phenomenon. At the same time, these researchers think that humans are now more capable of adapting to and mitigating droughts [1].

Droughts that extend over centuries are known as megadroughts. The effects of prolonged drought and megadrought can radically alter regional ecosystems and the human settlement within a region, and although a megadrought may speed up the process of desertification in marginal, vulnerable lands, the presence of a megadrought is unrelated to deserts per se.

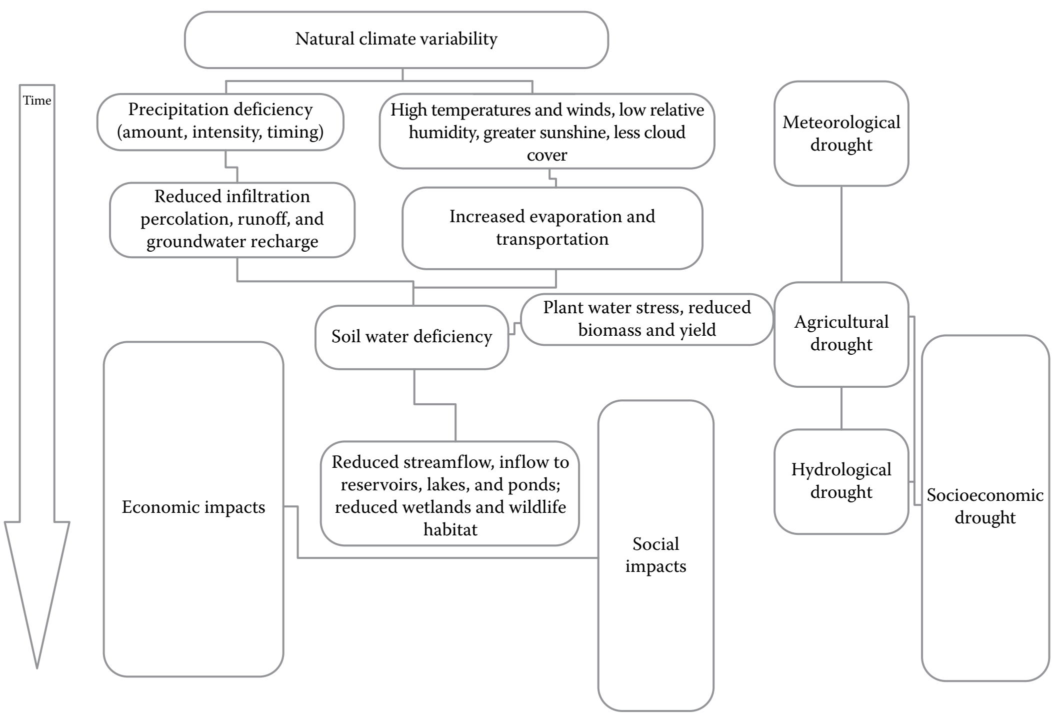

FIGURE 2.1 The relationship between meteorological, agricultural, hydrological, and socioeconomic droughts and their impacts. (Adapted from http://drought.unl.edu/DroughtBasics/TypesofDrought.aspx, a part of the National Drought Mitigation Center [59].)

2.1.5 Desert versus Drought

Drought is a natural disaster that strikes a region for a relatively short period of time compared with the Earth's long history. Droughts can last years, and megadroughts can last hundreds of years. That does not make the regions that experience these phenomenon deserts, however. Deserts can experience droughts, and droughts can provoke desertification of nondesert regions. Droughts can affect crop production, soil quality, disease spread, and groundwater availability, leading to economic, social, and political problems [64]. Deserts are the regions of the Earth that experience extreme dryness, often accompanied by high daytime and cool evening temperatures, although not always. Some desert regions exist in the Arctic and other cold regions. Most deserts do receive some precipitation, albeit sparse.

Definitions of deserts "rely on some combination of the number of days of rainfall, the total amount of annual rainfall, temperature, humidity, or other factors" [12]. The widely accepted, precipitation-based classification of desert regions is grounded on the work of Peveril Meigs, who stated that "extremely arid lands have at least 12 consecutive months without rainfall, arid lands have less than 250 millimeters of annual rainfall, and semiarid lands have a mean annual precipitation of between 250 and 500 millimeters. Arid and extremely arid lands are deserts, and semiarid grasslands generally are referred to as steppes" [63] (Table 2.1).

As water resources are depleted, water rationing or recommendations for reduced water consumption may be introduced. The United Nation (UN)'s Water for Life Decade website reports that water scarcity affects every continent and that more than 2.8 billion people experience water scarcity for at least part of each year, with another 500 million closely approaching water scarcity. Growing water use, now increasing at twice the rate of population growth, is partially to blame. The number of regions facing water scarcity is increasing, but not for lack of freshwater—mismanagement, contamination, uneven distribution, and climatic factors, including drought, all play a role.

There are eight UN Millennium Development Goals related to water scarcity:

MDG 1: Access to water for domestic and productive uses (agriculture, industry, and other economic activities) has a direct impact on poverty and food security.

MDG 2: Incidence of catastrophic but often recurrent events, such as droughts, interrupts educational attainment.

MDG 3: Access to water, in particular in conditions of scarce resources, has important gender-related implications, which affects the social and economic capital of women in terms of leadership, earnings, and networking opportunities.

TABLE 2.1 Comparing Droughts and Desert Conditions

	Drought	Megadrought	Desert
Duration	Temporary	Temporary, but may last for hundreds of years	Permanent
Indicators	Emerge slowly	Emerge slowly	Always evident
Land	Nutrient rich	Nutrient rich at the start, but may become nutrient deficient over time	Nutrient deficient
Agricultural productivity of the land	Lower than normal	Lower than normal	Very low to nonexistent
Conditions reversible?	Once drought ends, land normally recovers	Once drought ends, land normally recovers, although lasting effects may be observed	Conditions are normally permanent

Sources: ESCWA, *Vulnerability of the Region to Socio-economic Drought*, Economic and Social Commission for Western Asia, United Nations, New York, 2005; UNISDR, *Drought Risk Reduction Framework and Practices: Contributing to the Implementation of the Hyogo Framework for Action*, UNISDR, Geneva, Switzerland, and the National Drought Mitigation Center (NDMC), University of Nebraska-Lincoln, Lincoln, NE; WMO, Drought monitoring and early warning: Concepts, progress and future challenges, WMO Report No. 1006, 2006; Walker, M.J., *Hot Deserts: Engineering, Geology and Geomorphology: Engineering Group Working Party Report*, Geological Society of London, London, U.K., 2012.

MDGs 4 and 5: Equitable, reliable water resources management programs reduce poor people's vulnerability to shocks, which in turn gives them more secure and fruitful livelihoods to draw upon in caring for their children.

MDG 6: Access to water, and improved water and wastewater management in human settlements, reduces transmission risks of mosquito-borne illnesses, such as malaria and dengue fever.

MDG 7: Adequate treatment of wastewater contributes to less pressure on freshwater resources, helping to protect human and environmental health.

MDG 8: Water scarcity increasingly calls for strengthened international cooperation in the fields of technologies for enhanced water productivity, financing opportunities, and an improved environment to share the benefits of scarce water management [58].

2.2 Drought Management

Decision-makers at all levels of society can take steps to mitigate the effects of drought. Knowing the historical precedent for drought in a region is a major part of this effort, as is tracking weather systems, conditions, crop yields, water table levels, and other data to spot the early signs of drought, and adjust policies and plans to mitigate the effect of this phenomenon. To cope with a drought, societies must analyze the effects of a drought and determine plans of action. Many pressures influence how policy responses are crafted, and hence, they affect a country's long-term ability to plan for recurrent drought or megadrought (influenced by Conca and Dabelko [13]):

Pressure of immediate crisis: Politicians experience public pressure to prioritize mitigating the current and immediate effects of crises such as major droughts. This prevents and detracts from analyses and long-term planning for future droughts; once normal rainfall levels resume, they ease pressure on decision-makers, who typically read this as a signal to return to "business as usual."

Pressure for immediate results: From a hydrological perspective, politicians have a planning horizon that is often too short to devise long-term policies; they are also required to manage water resources in a way that is sustainable.

Single-sector policy planning: Government ministries are frequently plagued by static thinking and organized according to the territorial nature of human beings. Often, water-related decisions in one ministry are not coordinated with others whose portfolio includes water as well.

Drought early warning detection systems involve monitoring certain indicators that are associated with the major effects of lower rainfall, as well as socioeconomic indicators such as the vulnerability of food production systems, food security, availability and access to drinking water, access to fodder for livestock, food prices, and population migration patterns and trends [19].

Countries that are at risk for drought should design and operationalize a drought early warning system. A drought early warning system includes comprehensive and integrated drought monitoring for appropriate indicators and thresholds and involves gathering data that identify trends in climate and water supply (Table 2.2). Such a system makes it possible to observe the probability for drought and to forecast its expected severity. And the acquired knowledge base can be delivered to stakeholders in a timely manner which allows decision-makers to enact preemptive measures to mitigate the impacts of droughts by, for example, identifying vulnerable areas or susceptible economic sectors. Stakeholders must "be involved from the early stages of product development to ensure that the information will serve their varied timing and content needs" [74]. In some developing countries, rural areas tend to be geographically, politically, and economically marginal; hence, they do not garner the attention of decision-makers who reside in well-serviced urban centers. These farming stakeholders are often excluded from the decision-making process, a reality that complicates efficient responses to droughts.

Droughts are natural climatic variations and affect many aspects of human activities. Drought risk mitigation strategies therefore require long-term commitment and need to be mainstreamed into a country's

TABLE 2.2 Elements of Effective Early Warning Systems

Risk Knowledge	Monitoring and Risk Warning Service	Dissemination and Communication	Knowledge and Preparedness to Act
Systematically collect data and undertake risk assessments	Develop hazard technical monitoring and early warning services	Communicate risk information and early warnings	Build national and community response capabilities
• Are the hazards and the vulnerabilities well known? • What are the patterns and trends in these factors? • Are risk maps and data widely available?	• Is there a scientific basis for predicting the risks faced? • Are the right things being monitored? • Can accurate warnings be made in a timely fashion?	• Do the warnings reach all those at risk? • Do people understand the risks and warnings? • Is this information useful? • Does it enable proper responses?	• Are response plans up to date and tested? • Do people understand their risks? • Do people respect the warning service? • Do people know how to react to warnings?

Source: UNISDR, Platform for the promotion of early warning, Basics of early warning, http://www.unisdr.org/2006/ppew/whats-ew/basics-ew.htm, 2005.

development agenda. A UN report lays out a framework for drought risk reduction that is anchored in the following steps (based on UNISDR [60]):

1. *Policy and governance*: Senior-level decision-makers' political commitment is critical to the development and success of mitigation strategies. This often requires knowledge development and institutional establishment. Drought-relevant policies need to be informed by scientific data and input from below and to emphasize risk reduction, which includes prevention, mitigation, and preparedness. They require the development of requisite institutional mechanisms (policy, legislative, and organizational) that can craft and implement drought risk reduction policies.
2. *Drought risk identification and early warning*: The hazards droughts produce are related to their intensity, duration, and spatial extent and are affected by environmental, economic, and social vulnerabilities of the affected population. Drought monitoring, early warning systems, and impact assessments are critical in identifying potential socioeconomic risks and in assessing and managing them. Climate change has made this task much more complex.
3. *Awareness and education*: Drought-related awareness helps develop a "culture of disaster prevention and resilience" through effective communication between academic specialists, decision-makers, and various community stakeholders. This involves gathering, analyzing, organizing, and sharing data on a drought and its potential impacts, as well as building people's capacity to plan for and respond to a drought event. This type of education needs to be interactive. People and institutions should learn from one another, and local, traditional knowledge should also be integrated.
4. *Reduction of background drought risk factors*: Local drought vulnerability must be reduced by dealing with background factors, including poverty reduction, and by embracing sustainable land use planning and post-disaster recovery planning measures. Special attention should be paid to the security of vulnerable high-risk groups (elderly, disabled, low-income residents, and others).
5. *Mitigation and preparedness*: Developing and implementing effective mitigation and preparedness policies requires bottom-up approaches, such as identification of local needs and integration of indigenous knowledge, and top-down approaches, such as institutional capacity building. In other words, communities should not rely solely on after-the-fact emergency response measures.

Technological adaptations to droughts include policies that incentivize the acquisition and use of water-efficient appliances and devices such as the installation of low-flow faucets and toilets. In recent decades, numerous technologies to monitor the onset of drought have been developed. A system that uses an online "remote sensing database to monitor drought development through continuous assessment of the condition of ground vegetation" was developed. This prototype was implemented in South and West Asia and may be improved and replicated in different regions of the world [36].

In 2002, NASA launched two satellites that map changes in the Earth's gravitational field. The GRACE (Gravity Recovery and Climate Experiment) mission provides insights into diverse fields of research, including hydrological indicators, such as groundwater storage, and volcanic (and magma) activities. "GRACE is revolutionizing how droughts can be tracked, quantifying their beginning, their ends" as well as droughts' "instantaneous magnitude" [3]. These and other technologies vary in their spatial coverage, as well as the cost, timeliness, and the user-friendliness of the data being generated.

2.3 Impacts of Droughts

Droughts affect all aspects of life in human and natural systems. Their effects may be economic, environmental, and social. The former includes the financial cost of reduced hydroelectric power generation or the cost associated with irrigated versus rain-fed agriculture. Poor pastures may force farmers to sell their livestock at a loss and, resultantly, lower-income residents may have to pay more for food. The environmental impacts of droughts include damage to the ecosystem, such as lower amounts of food or water available to wildlife, loss of wetlands, destruction of habitat, and erosion of unprotected topsoil. Finally, social impacts include reduced crop yields, lower incomes, and, in some cases, the loss of human life.

2.3.1 Ecological Impacts of Droughts

When a period of drought exists, the effects on the ecology of a region can be drastic. Freshwater fish rely on stable water supplies of certain quantity and quality, and as the water level drops in ponds, lakes, streams, and rivers, resource pressure increases. In addition, food supplies diminish and rates of diseases increase. In closed systems such as lakes and ponds, over time, the confined space and increased resource pressure can combine, potentially leading to species endangerment and, potentially, the extinction of some species found only within the affected system.

What happens with aquatic life happens with animals and plants, as well. Although some species are able to adapt to lower precipitation levels, many are not. In addition to the changes in food supply and the potential migration of animals that are capable of leaving a drought-stricken area, drought can also alter the soil quality of a region. Salts infiltrate the soil, reducing agricultural productivity. At the same time, wind erodes the existing topsoil. As water and crop yields drop, and livestock struggle to find adequate roughage, people will have difficulty finding the sustenance or labor force necessary for farming activities. As a result, famine may develop.

2.3.1.1 The Sahel: An Example of the Ecological Impact of Prolonged Drought and Megadrought

On the edge of the Sahara Desert, one striking example exists of the potential damage that prolonged drought can wreak on a region. Known as the *Sahel* ("coast" in Arabic), this semiarid region is frequently used by local peoples for agriculture and livestock grazing. In the 1970s, a decade-long drought started here and killed 100,000 people before it ended [7].

Part of a larger climatic cycle, the Sahel's recent drought will likely repeat in the next few decades. Evidence of similar droughts lasting several decades or more extends hundreds of years in the region's soil records and can also be observed in the presence of trees that stand in the middle of Ghana's Lake Bosumtwi. The trees flourished, growing in the center of a former lakebed during a drought that dried the lake completely and left fertile soil behind. The drought itself likely lasted 350 years, from 1400 to 1750 [53]. Today, the lake has returned and the tree trunks are visible above the water in the center of the lake.

In a 2009 study, Shanahan et al. linked Atlantic Ocean surface temperatures to changes in the Sahel's climate and showed that ocean warming correlated well with the existence of drought in the region [53]. As climate change warms the world's oceans, the Sahel is placed at greater risk of drought.

2.4 Responses to Drought

Many different factors affect how governments and people respond to drought. Some climate models make dire predictions, as they "project increased aridity in the 21st century over most of Africa, southern Europe and the Middle East, most of the Americas, Australia, and Southeast Asia. Regions like the United States … might see persistent droughts in the next 20–50 years." Therefore, climate change adaptation measures need to factor in the likelihood of "increased aridity and widespread drought" in coming decades [16].

Governments, corporations, communities, and individuals respond to droughts in their own capacities and, hence, in different ways. Governments initiate water-saving projects such as building sewage treatment facilities and, in some cases, desalination plants. Other measures include strict water rationing in domestic, industrial, and agricultural sectors, as well as rural–urban water reallocation, which may create or exacerbate political and social tensions between the center and the periphery.

Water rationing or government regulations may compel farmers to only irrigate high-value crops, especially those that do not require high-quality freshwater. The severity and duration of a drought will affect whether a farmer decides to abandon agricultural pursuits in favor of employment opportunities in large urban areas. When anticipated opportunities do not materialize, some of these internally displaced former farmers may become involved in criminal activity or organize action against the government; the latter is usually in the form of mass protests, which could foment political instability, especially in politically fragile states. If grievances are not addressed by the government, political violence and international water refugee migrations may result as people struggle to find a safe place with sufficient water to live in. The World Development Report [70] asserts that "low incomes reduce the opportunity cost of engaging in violence." Consequently, the economic impacts of droughts have the potential to destabilize communities and, in turn, to affect domestic and international political systems.

Water-related data make it easier to manage and adapt to droughts when they occur. The more detailed the database is, the more tailored policies can be. For example, smart water meters can continuously log water consumption. The accumulated data through such meters make it possible to investigate the effectiveness of water demand management strategies through comparative analyses of consumption patterns in certain periods and across sociodemographic groups [25,69]. Understanding water use patterns "can help identify conservation potential and appropriate instrument for implementing conservation measures [25]." Because of their ability to identify consumption patterns on micro- and macro-levels, smart water meters make it easier for decision-makers to more accurately forecast end-user demand and to design more effective water conservation policies.

The agricultural sector is by far the largest user of water; even relatively small improvements in irrigation efficiency can potentially yield immense savings that can be allocated elsewhere. Drip (or micro) irrigation delivers water and, if needed, fertilizer to a plant's soil surroundings. This results in water savings that range from 40% to 80% compared with conventional irrigation methods. Yield increases may reach 100%. The significant labor savings resulting from a reduced need to haul water often benefit women and girls, and environmental benefits such as reduced fertilizer and pesticide application are also products of this irrigation method. The "impact of this technology has been limited in sub-Saharan Africa by reliable access to water" and the absence of agricultural and technical support services [11,42]. Solar-powered drip irrigation systems are a recent innovation that, according to Burney et al. [11], can significantly increase the reliability of access to water, especially in remote, off-grid areas. Burney et al. also argue that this easy-to-maintain system is battery-free, thus bypassing the typical weakness of photovoltaic (PV) use in developing countries.

In debating human impacts on the natural environment and responses to it, cornucopians have long argued that people would embark on technological innovations that would ensure humanity's continued survival and prosperity. History has shown that mass adoption of beneficial new technologies is harder than it seems; politics, culture, and economics play deciding roles. In addition to the availability of such technologies, Zilberman et al. [76] argued that what "trigger[s] technological and institutional changes" are "extreme events." They added, "[M]any of the most important institutional changes affecting U.S. agriculture have been the results of extreme events, such as the Depression and the dust bowls of the 1930s."

Although humans may need to look into the abyss before they undertake the necessary, sometimes radical measures, drought-susceptible regions of the world are better off crafting rational institutional designs—ones that slow the onset of drought and deal with it after it descends on an area. Ironically, a drought can also be seen as an opportunity to enact the necessary transformative measures that would minimize the adverse effects of similar events in the future.

Enacting appropriate preemptive policies to mitigate the effects of drought requires balancing competing demands. In the Mekong River basin, Heikkila et al. [32] found that droughts adversely impact crop production, hydropower, and fisheries, yet how they affect society, economy, and ecosystems is "highly unpredictable." Another complication is that, compared with a flood event, the effects of a drought are quite diffuse, less visible, and emerge slowly.

Institutional factors affect responses and adaptations to droughts. Formal and informal institutions, as well as (in)visible engagement, are likely to be deployed to mitigate the effects of a drought. Effective institutions need to be responsive to people's needs, integrate input from multiple locations and geographic and social scales, and engage related decision-making institutions that may affect policy design. For institutions to be proactive and withstand the test of time, they need to be designed with foresight through a public participation process and need to include the flexibility to integrate new information.

2.5 Impacts of Drought on Agriculture and the Population

When confronted with the environmental stressors that drought conditions produce, humans react. The economic challenges that accompany a drought force people to adapt by doing jobs that they would otherwise avoid, including selling firewood (this could, in some areas, contribute to desertification), and by reducing the quantity and quality of their diet. Those who do not foresee relief on the horizon are forced to abandon their drought-stricken area for the promise of a better life in a nearby urban center or another country.

Typically, the most vulnerable in society are the poorest of the poor who tend to live off the land, often as subsistence farmers, and have minimal assets for emergencies. For example, in 2015, Ethiopia experienced a drought so severe that the number of people who were in need of food assistance rose from 4.55 million in August to 8.2 million in October. The country's problems are compounded by the fact that over 80% of the "population works in agriculture, which makes up about 40 percent of the nation's economic output. That makes the country especially vulnerable to drought and the effects of climate change [22]."

The UN High Commissioner for Refugees reported on the drought that hit Somalia in 2011 and quoted a refugee who had made it to Kenya as saying: "My home is nothing but dust and starvation. I cannot go back there [5]." Nature has forced hundreds of thousands of Somalis to seek asylum in nearby Kenya. Hardest hit are the people whose livelihood is based on herding animals. Some have watched their goats and cows fall ill and die "one-by-one as the worst drought in memory denied the animals water and feed. The livestock were in many ways considered to be part of his extended family and their loss was catastrophic. When the last cow died, everyone knew that the children would be next [5]."

While a natural disaster ruined many lives in Somalia, the consequences of Sudan's drought were aggravated by tradition, political manipulation, and neglect by the central government. The conflict in Darfur, Western Sudan, pitted settled farmers against the Arab nomadic pastoralists. The latter traditionally grazed their camels and fed "their stock on the leavings from the harvest" of the farmers who "would share their wells." The long, amicable relationship between the nomads and the sedentary farmers was disturbed by the drought. As the rains began to fail, sand started blowing into fertile land and wind eroded alluvial soil. The farmers, who had once hosted the Arab nomadic tribes and their camels, "were now blocking their migration; the land could no longer support both herder and farmer [21]."

While some herders adapted by becoming settled farmers, others "stuck to their fraying livelihoods." This refusal to adapt is related to the fact that the people's lifestyles are central to their cultural identity as "Arabs" and "Africans" of Darfur. The people are physically similar but culturally distinct; the former are mostly camel herders and the latter are farmers. This difference in lifestyle is therefore central to the identity of each group. In the late 1980s, the "landless and increasingly desperate Arabs began banding together to wrest" lands from the farmers, which triggered violent confrontations between the two groups [21].

2.5.1 Domestic Crop Production

Physical water scarcity, or water scarcity that results from geographic location of drought, is prevalent in the tropics, South Africa, Madagascar, and parts of Australia, although it occurs in other regions as well. At any given point, 700 million people experience water scarcity, and by 2025, an estimated 1.8 billion people will likely be living in absolute water scarcity. According to the UN [58], "With the existing climate change scenario, almost *half the world's population* will be living in areas of high water stress by 2030, including between 75 million and 250 million people in Africa. In addition, water scarcity in some arid and semi-arid places will displace between 24 and 700 million people." The organization views the problem as so important that it has produced more than a dozen reports and working papers on water scarcity between 2003 and 2014.

Much of the Arab world is below the water poverty line, and as of 2011, many agricultural policies, combined with increased urbanization of Arab countries, have exacerbated the problem. Kuwait and the United Arab Emirates are particularly affected [39]. In 2006, Syria was under slight water stress. That situation changed with the 2008–2011 drought in the region, something scholars like Gleick find to have partly contributed to the political violence and civil war in Syria. The situation is not likely to improve in the near future as water shortages are expected to continue for the next 25 years. The Tigris–Euphrates Basin is losing water faster than any other region in the world, and some of the existing freshwater sources in Iraq are also polluted by sewage and drainage dumping into the Tigris River [27,57].

Globally, water scarcity is projected to worsen as a result of droughts, climate change, and other pressures on available supplies. Scientists suspect that climate change and drought in parts of India, China, and the southwest United States could lead to a 40%–70% increase in water stress by 2040. Chile, Estonia, Namibia, and Botswana are expected to see significant water stress increases [57]. Human-caused drought is likely to affect many regions, including large parts of the Middle East, as groundwater resources are depleted or polluted. As a result, agricultural production may decrease in areas where water supplies are no longer available or where agriculture becomes impractical [34].

The government of Yemen has contemplated moving the capital city in response to heat, water scarcity, and drought. Many Middle Eastern and North African governments, such as Israel, Syria, Abu Dhabi, Turkey, and Algeria, have been forced to adapt to recent heat waves and drought. Hundreds of people in the region have died from these conditions, and "many smaller cities have run out of water completely [57]."

Droughts may result in policy changes that limit the amount of water a household can receive by the number of occupants. Other potential policy responses include higher water prices as water poor countries import water to provide for their population's needs. Some regions may eventually become uninhabitable, and heat-related or drought-related deaths may occur in areas that are particularly water poor.

Decreased food production is an important effect of drought; however, industrialized countries can often use technological prowess, economic health, and institutional strength to accommodate for lower precipitation levels. Still, even industrialized nations can suffer greatly in drought. During the Great Depression, the center of the U.S. corn and wheat agriculture was hit by severe drought. The region formerly known as the "bread basket" earned the moniker "the dust bowl." This agricultural downturn, coupled with economic misfortune, increased unemployment as farmers abandoned their lands after being unable to pay for them or maintain their operations. This, combined with other socioeconomic and political circumstances, resulted in one of the most tragic and memorable periods in American history [43,48].

More recently, drought in California made international headlines as the "salad bowl" of the United States struggled to adapt to a drastic drop in regional rainfall. According to AghaKouchak et al. [1], "California … fields have had to be left fallow, contributing to statewide losses of US$2.2 billion in 2014. More than 12 million trees have died, with cascading impacts on amphibians, birds and mammals. Streams and wetlands are drying up, including the American River hatcheries of steelhead and Chinook salmon. More than 17,000 jobs have been lost, mainly in poor rural communities."

Many Western countries have fewer farmers as a percentage of the population, a result of the industrialization of agricultural production. Their economies are, perhaps as a result, more robust against shocks generated by drought. On the other end of the economic spectrum, subsistence farming is common. Individuals in countries that are not industrialized or only have limited commercial production must rely on their ability to work the land and raise food crops and livestock. Subsistence farmers, due to their reliance on what their own farms can produce and their economic position, are particularly vulnerable to the impacts of drought.

> The most vulnerable amongst those hit by drought will be those with few assets to sell, those who most need to purchase grain due to an absence of their own household reserves and those who cannot pin access to food through other means, such as borrowing, coercion or theft. The richest members of the community may even be in a position to benefit during drought, as they can acquire land and other assets at low prices from distress sales by poorer neighbours … an individual's entitlement to food depends not only on direct output of crops, etc. but also on his access to food through the market, by the sale of labour or other commodities and through non-market mechanisms, such as redistributive systems within society. In times of drought, not only is there a direct shortfall of food production but also relative price movements of grain versus other commodities may drastically reduce the purchasing power of groups. Ibis is seen in the case of pastoralists who face rising grain prices but failing livestock prices as drought intensifies. Pastoralists face a major decision problem related to the timing of sales which minimize unfavourable grain/livestock ratios. Many farmers may be in a similar situation, needing to sell livestock, labour or land in markets where an excess supply of these commodities has reduced their value [56].

Drought's impacts on food and agriculture are often the precursors for greater problems, as the chart in the beginning of this chapter shows. The 2007–2010 severe drought in Syria likely contributed to the violent conflict that continues to envelop the country, in part as a result of the mass migrations to urban centers that it provoked [40]. Other potential ramifications of drought on food and agriculture include reduced crop yields, resulting in famine, malnutrition, and other health crises; economic downturns in agriculturally dependent countries; and political instability. Some scholars suggest that crop failures in 1788 and 1789 contributed to the peasant revolts in the French Revolution that took place at that time [65]. Food and agricultural production may be the hardest-hit sectors during a drought and likely contribute to the severity of other drought impacts.

2.5.2 Failure and Famine

The vast majority of water conflicts are resolved peacefully, but not all. It is reductionist, simplistic, and deficient to explain events such as civil war or transnational war with a single factor like a drought. Furthermore, although the relationship between drought, water, and violence is rarely a linear one, it is real, multifaceted, and usually oblique. As illustrated by examples throughout this chapter, the impact of drought on farming and pastoral practices may play a role in conflicts that do erupt.

The link between droughts and conflicts is the subject of some debate in the literature. A study by Theisen et al. [55] finds "little evidence" of a connection between drought and conflict. Yet, it also finds "ethnopolitical exclusion is strongly and robustly related to the local risk of civil war." Environmentally triggered adversities like droughts amplify societal divisions, affecting marginalized groups the most, who have the least amount of assets to leverage in emergencies, which leaves them with few, if any, alternative means of making a living. Their plight contributes to societal upheavals, disturbances, and violence.

This was precisely the case in the Syrian civil war. Gleick [27] found that the multiyear drought that blanketed the eastern Mediterranean Sea countries decimated crops and wreaked havoc in the livelihoods of rural communities, which forced many unemployed farmers to seek opportunities in cities. This was one of the factors that led to the Syrian civil war, which started in 2011. Another illustration can be found in the states of Karnataka and Tamil Nadu in India, where a conflict that has claimed lives, left politicians frustrated, and stretched for over a decade began with the simple act of changing water allocations. Farmers and residents who knew their livelihoods would be affected reacted angrily, and over a dozen lives have been lost so far in the conflict [28].

Agricultural crops require specific amounts of water to grow. Higher-yielding crops frequently consume more water. In times of drought, the normally advantageous trait of high-yield production becomes a disadvantage. Plants struggle to stay alive in the heat and yields decrease and in some cases fail completely. Highly heat-sensitive crops include the following [54]:

- Alfalfa
- Banana
- Beans
- Maize
- Onion
- Peas
- Pepper
- Potato
- Spring wheat
- Sugar cane
- Tomato
- Watermelon
- Winter wheat

Many of the aforementioned crops are dietary staples in different parts of the world. Extended crop failure in regions where importation markets are not strongly established can lead to famine. Livestock and human malnutrition can result. Food prices globally can be impacted by crop failure in regions that traditionally produce high amounts of agricultural products for export, and as a consequence, the price of agricultural products can drastically increase on a global scale. In 2008, food riots erupted in Ethiopia as a result of drought and increased food prices. Violent riots occurred in 13 other African countries between 2007 and 2008 as a result of rising food prices, and in 2010, "a longstanding drought in Niger destroyed harvests, which was then followed by unprecedented heavy rains, killing livestock and creating what was described by the United Nations as the worst food crisis in the country's history [6]."

Scientists and policy makers are developing ways to mitigate crop failure and prevent famine, in part by creating drought-resistant crops. Rice, corn, and soy are a few of the major staple crops for which drought-resistant varieties exist [23,41]. Additionally, some researchers are focusing on optimizing soil moisture through carefully controlled irrigation.

In China, a team of scientists discovered that the optimal soil moisture for microbial biomass carbon content was 19.5% for maize in the region they studied. In times of drought, soil moisture below 14.3% demonstrated alterations to the microbial composition, and in severe drought stress, when soil moisture fell below 10%, the microbiome of the soil had difficulty recovering [23]. The microbial biomass carbon content demonstrates the microbial health of the soil, and healthy soil is necessary for the production of food crops. Geng et al. [23] suggested that soil moisture be kept above 14.3% to ensure optimal grain output in maize fields.

Not all crops require the same moisture levels, but Geng et al.'s [23] research is an important step toward identifying how farmers can improve yield and irrigate wisely, even in times of drought. If watering is constrained using soil monitors and irrigation takes place only when necessary, crop yield can theoretically be improved while water waste is simultaneously reduced.

2.5.2.1 Water Shortage and Scarcity

Crop failure and famine are not the only results of drought. Water shortages that affect the daily life and hygiene of humans can also result from this phenomenon. In order to maintain health and hygiene, humans require a minimum of 7.5–15 L of water per day for drinking, cooking, and basic hygiene [72]. In times of drought, it may be difficult, if not impossible, to obtain the necessary amount of water.

In Western countries, water usage tends to be high, making it potentially harder for citizens in countries such as the United States to adapt to severe drought. According to Pennsylvania's North Penn Water Authority [51], "two thirds of the water used in a home is used in the bathroom. Nearly 40% gets flushed down toilets; more than 30% is used in showers and baths. It takes 2 gallons to brush your teeth, 2–7 gallons to flush a toilet and 25–50 gallons of water in a five-minute shower." In the Middle East, where the government's water subsidies have cultivated a lifestyle that the region's resources cannot support, the situation is even worse. "Per capita water use in the United Arab Emirates (UAE), for example, is about four times that of Europe; consumption in Abu Dhabi is 550 liters of water per person per day, two to three times the world average of 180–200 liters [34]." Unsustainable water consumption can have many sociopolitical ramifications, from water rationing to the potential for political instability and even conflict over water resources. The political effects of a drought are evident in many places, especially in the Darfur conflict.

2.5.2.1.1 Livestock

Livestock are heavily affected by water scarcity and may be the first to experience the negative effects of drought. Forage decreases and livestock may become malnourished as droughts set in. Additionally, as water shortages spread, farmers may reduce the amount of water their stock receives or sell nonvital stock in an attempt to provide the water their families require [56]. As a result, meat and milk supplies may also decrease in quality and quantity in times of drought. One exception may be camel's milk. A 1980 study reported:

> At the end of each dehydration period there were increased water percentages in the milk when compared with milk of hydrated camels. The content of fat, lactose and protein declined. Concentrations of Na, K, phosphate and chloride in milk increased while Ca and Mg concentration declined. The urea concentration of the milk was unchanged … It was concluded that the milk of dehydrated camels is an excellent human food in arid areas, as the water and salt content are high while the nutritive value remains good [75].

Cattle, on the other hand, may be culled in response to drought. Their need for feed and hydration makes it difficult to manage a large herd during severe drought, even in industrialized countries such as Australia [30].

In response to the potential for significant drought-related impacts on livestock and agricultural production, several global research projects are underway, some of which offer practical solutions. Two programs of particular importance are the Consultative Group on International Agricultural Research (CGIAR)'s Comprehensive Assessment of Water Management and Agriculture and the Challenge Program on Water and Food. Both provide significant data on the management, development, and conservation of water in developing countries, with ideas for the implementation of smart water usage for agriculture.

2.5.3 Drought-Induced Migration and Drought Refugees

When a drought-afflicted population is capable of moving to find access to water, the impacts of this natural phenomenon may lead to water refugee movements. In 2003, the number of water refugees was 25 million—so high that the UN declared it the "International Year of Freshwater" in an attempt to focus on key water problems, such as drought and water-borne diseases. Despite international efforts to address the situation, as of 2005, there were more water refugees than war refugees [17].

Drought-related water refugee movements arise from unexpected places. Although drought is commonly associated with semiarid and arid climates, "deforestation leads to drought and disrupts the hydrologic cycle in tropical rainforests by reducing the evaporative cooling facilitated by mist canopy cover, e.g. rice [8]." Even rainforests, therefore, are subject to drought.

According to the U.S. National Center for Atmospheric Research (NCAR), the percentage of land affected by serious drought more than doubled between the 1970s and 2005. A report released in 2007 by Christian Aid suggested that one billion people could become water refugees in the near future, many of them as a result of water loss. A more modest figure suggests that by 2050, up to 50 million migrants will flee their homes in response to drought [45]. By 2050, five times as much land could be under extreme drought as in 2007, and 1.7–1.8 billion people could be living in dire water poverty. Hence, they may be forced to relocate [4,58].

Earlier in this chapter, we touched on the potential internal displacements that can occur when farmers and agricultural workers abandon the farming sector in search of greater economic opportunities and ready water supplies as a result of drought. One striking example of this phenomenon is the mass migration of nearly three million residents of the southern Great Plains of the United States to other parts of the country during the Great Depression—as the "dust bowl" grew drier, farmers and agricultural workers fled with their families. A longer, slower, and similarly motivated migration is the flight of rural Mexicans to the United States in response to increasingly dry and unfarmable land conditions [10].

Cities like the capital city of Quetta, Pakistan, which relies on what is believed to be a fossil (nonreplenishable) aquifer, may become ghost towns as water supplies dry up, leaving millions of residents homeless. Parts of India, Mongolia, Nigeria, and Iran have already seen entire villages disappear (more than 88 in Iran alone), and parts of Mexico and China may face similar fates. China has already recognized the presence of desert refugees fleeing from expanding desert regions in three of its provinces [10].

Environmental refugees flee their homes in response to numerous disasters, but droughts are a major driving force behind human migrations. Refugee camps in Kenya are filled with Somali and Ethiopian refugees who fled a range of factors in their homelands, one of which was drought. More refugees leave drought-stricken locations every day, and the current population of these camps is more than 180,000 [49].

In addition to population movements arising from the phenomenon of drought itself, refugees are also created as a result of political violence that results from water scarcity and drought. Many refugees fled the Horn of Africa in response to water shortages and political violence. The vast majority of climate refugees remain internal migrants however, seeking safe places to live in, in their own country. According to António Guterres, the U.N. High Commissioner for Refugees, as quoted by National Geographic Education [49], "Climate change can enhance the competition for resources—water, food, grazing lands—and that competition can trigger conflict."

Drought can affect entire countries or large portions of countries, which may in part lead to the creation of environmental migrants at a rate higher than many other natural or climate change-related disasters. By 1995, 10 million environmental refugees or migrants had fled the Sahel region in response to extreme drought. They made up 40% of the environmental refugees noted during that year [45].

Unfortunately, the legal status of "refugee" is limited to individuals who can prove that racial or ethnic discrimination led them to flee their home. As a result, refugees who flee their countries as a result of drought do not have the same legal protections as political refugees [37].

2.5.4 Heat, Water, and Health

"Drink eight 6–8 ounce glasses of water each day." If you live in the United States, you have probably heard that phrase more times than you care to remember. From childhood, we are taught to appreciate our body's need for water and water-rich food sources.

As supplies of drinking water dwindle in severe drought, water rationing may begin. This could force people to sacrifice hygiene for hydration, which could have adverse consequences on health. Infectious diseases, malnutrition, and other health problems are frequently exacerbated by drought.

The hot, dry conditions that most often lead to drought can also lead to many heat-related illnesses, such as sunburn, heat cramps, heat exhaustion, heat stroke, and dehydration. Heat stroke and dehydration are potentially fatal if left untreated. Agricultural workers and farmers are particularly vulnerable to these conditions.

Another health condition to keep in mind is stress; as drought sets in, psychological and physical stress can exacerbate the already-difficult situation of drought.

There are many ways that drought can increase disease in affected regions. According to the U.S. Centers for Disease Control and Prevention (CDC), infectious diseases, chronic diseases, and diseases transmitted by animals and insects are all affected by drought:

Increases in infectious disease can be a direct consequence of drought.

- Viruses, protozoa, and bacteria can pollute both groundwater and surface water when rainfall decreases. People who get their drinking water from private wells may be at higher risk for drought-related infectious disease. Other groups also at increased risk include those who have underlying chronic conditions.
- Acute respiratory and gastrointestinal illnesses are more easily spread from person to person when hand washing is compromised by a perceived or real lack of available water. During water shortages, the risk for infectious disease increases when hygiene is not maintained.
- *E. coli* and *Salmonella* are examples of bacteria that during drought can more readily contaminate food and cause infectious disease. Food can serve as a vehicle for disease transmission during a drought because water shortages can cause farmers to use recycled water to irrigate their fields and process the food they grow … the likelihood of surface runoff, which can occur when rain fails to penetrate the dry and compacted soil that often accompanies drought, can cause the inadvertent contamination of crops.
- Other infectious disease threats arise when drought leads to the contamination of surface waters and other types of water that are used for recreational purposes … Persons exposed to contaminated recreational waters are more likely to become infected with pathogens that thrive in the shallow warm waters that exist during drought conditions [62].

In addition to these ways in which infectious diseases can spread, individuals with compromised immune systems may be more susceptible to infections due to contaminated water during times of drought. Changes in air quality during drought may affect allergy sufferers and people who have chronic respiratory conditions such as asthma. Stagnant or slowly shrinking bodies of water can make it easier for mosquitoes to breed and spread illness. Additionally, wildlife may seek out human settlements for accessing water, leading to more frequent encounters with humans and a greater likelihood of animal-borne diseases in humans. Farmers and herders may also migrate to larger settlements, bringing new germs with them and spreading diseases, albeit unwillingly [62]. If drought is not properly managed, it can become a public health catastrophe.

One of the deadliest companions of drought is malnutrition. Dwindling crops with rising prices and a decreased supply of animal protein combine to create a perfect nutritional storm for individuals who live in areas afflicted by prolonged drought. Among the highest causes of morbidity during drought, the World Health Organization (WHO) cites protein–energy malnutrition and various micronutrient deficiencies. Micronutrient deficiencies can aggravate or provoke illnesses such as iron deficiency anemia, scurvy, beriberi, pellagra, and measles, drastically increasing the mortality rates from drought in afflicted regions [73].

2.5.5 Insulating Economies from Drought: Farms First

Agriculture is one the first sectors affected by drought. Lower agricultural yields raise crop prices, which may result in hunger, and sometimes in deaths. Economic impacts of the 2015 California drought led to social and political conflicts in the state. Multiple stakeholders jostled for political influence as the state's officials attempted to balance ecological and economic interests and water [39].

2.5.5.1 Is Water a Right or a Commodity?

The Dublin conference on Water and the Environment [35] referred to water as an economic good. One of the Dublin principles states that "water has an economic value and should be recognized as an economic good, taking into account affordability and equity criteria." The idea is that by pricing water, market forces will allocate the resource to its best, most productive uses, with benefits to people, the environment, and the economy [9,35,52]. The economics of water play a large role in drought preparation, management, and recovery. If water is a right, how can it be ethically bought and sold? If it is a commodity, but one that is necessary for life, how is the market controlled?

In 2010, the UN General Assembly adopted a landmark resolution when it explicitly recognized the human right to water and sanitation. The decision acknowledges that access to "clean drinking water and sanitation are essential to the realisation of all human rights." The resolution also calls on governments and international organizations to work to "provide safe, clean, accessible and affordable drinking water and sanitation for all [47]." For this resolution to become a reality, some developing countries require a lot of assistance. However, "[f]or many of those who have access to water, it is either too expensive or [un] suitable for consumption, often exposed to dangerous levels of biological contaminants and chemical pollutants partly due to inadequate management of urban, industrial or agricultural wastewater. Simply put, for many people water is not yet a human right [61]."

In drought-prone regions, this is of particular concern. Water subsidization policies in many wealthy, oil-producing countries make water an easy resource to overuse, a practice that is not fitting with the region's limited water supplies [2,50]. Similar policies support the agricultural sector in drought-prone regions of the United States.

Water economic reform is one potential way to managing a drought. Educating the public as to the importance of saving water can be an extensive task and may take generations to make a measurable change. When drought and its effects are immediate threats, the luxury of time may not be available. Changing water prices for quantities above the amounts necessary for basic living can help to reduce excessive use for luxuries like watering a water-intensive garden or lawn or filling a swimming pool.

As conflict research demonstrates, the simple presence of resource scarcity does not generally lead to domestic or international conflict on its own—even when the resource in question is potable water. "Short-term disasters, however—floods, hurricanes, *droughts,* earthquakes, and major accidents—can contribute to major political conflicts if elites and popular groups blame the regime for causing them, or for a particularly poor or corrupt response [emphasis added] [29]." Goldstone [29] argues that most disagreements provoked by slow environmental changes are resolved through nonviolent means, while larger disasters give governments the opportunity to show their competence. Weak and corrupt governments are more likely to experience political violence after a natural disaster.

Water-related political violence occurs on multiple levels, from neighborhood fights to international wars. Maude Barlow discusses the creation of vigilantes in Sydney reacting to drought and water shortages, legal battles between states in the American West over the Colorado River, and the Darfur conflict, which erupted in part as a result of repetitive droughts in the region [4].

A World Bank [71] report finds that in Africa, droughts recur on such regular basis that "no region in Sub-Saharan Africa has been spared over the last three decades," with the most adverse effects being borne by the people whose livelihoods are dependent on farming or raising animals. It also reports that both droughts and floods are "occurring with increasing frequency, while the threat of conflict (both coming from within and spilling over from neighboring countries) continues, as demonstrated by the events over the last 18 months in the Central African Republic, Kenya, and Mali [71]."

The role of livestock in village economies is a subject of debate. Although inherently valuable, some researchers, including Fafchamps et al. [20], believe that their importance as an economic asset in times of drought is frequently overstated. Fafchamps et al. [20] discovered that livestock had a relatively small ability to protect West African villagers' incomes from the effects of drought. Farmers were able to sell their livestock to an extent, but it only accounted for 15%–30% of the income shortfall experienced in drought.

Although Fafchamps et al.'s [20] findings are not earth shattering, they do raise questions about how individuals in drought-prone regions insulate their economies against drought. Economic resilience is a major factor in maintaining political and social stability following a natural disaster, and decision-makers need to be aware of traditional and nontraditional methods for protecting village, regional, state, and national economies from these events.

Smart long-term planning and economic reforms that result from drought can have a positive economic impact and may even help economies to become more resilient to natural disaster. In the short term, however, drought can have an extremely negative impact on the economy. Droughts commonly provoke or exacerbate economic downturns, in some case decreasing the Gross Domestic Product (GDP) by up to 20% [26].

California's 2014 drought resulted in an estimated water shortage in excess of 1.5 million acre feet of water in the state's Central Valley [33]. In response to the projected shortage, decision-makers, public awareness groups, and the agriculture industry mobilized to minimize the economic impact of the drought. Another recent drought is fresh in their minds. In 2009, Californians watched 7,500 jobs disappear and 210,000 acres go fallow. Despite efforts to reduce the 2014 drought's impact on the local and national economies, the state projected an agricultural loss of $738 million, with an additional accumulated charge to farmers of $448 million for pumping water to agricultural sites. The state's GDP is expected to decrease by at least $855 million. As a result, household incomes in California may also decline by roughly $550 million dollars and job losses are projected to increase by up to 20% [33].

The economic impacts of drought are perceived at multiple levels of society, not just by farmers. Still, it is the farming sector that bears the brunt of drought. A study of the response to the 2009–2011 drought in China showed that only approximately 10% of farmers took steps to mitigate the drought's effects. Adaptation was not random, however. The authors reported, "[A]ssets at both household and community levels have significant effects on farmer's decision on taking physical adaptation measures against drought [67]." The economic impacts of drought therefore, as emphasized in several sections of this chapter, are influenced by socioeconomic status.

Taken together, the China and California examples show that even in Western countries that are well-accustomed to frequent droughts, the economic impacts can be significant. Economic downturns that result from drought are also likely to impact the poorest first and hardest. In a predominantly agrarian society, the effects can be detrimental.

One response to economic downturns is the creation and use of water markets. Although present in nondrought scenarios, water markets can facilitate drought mitigation by allowing water-rich regions to sell their freshwater resources to areas hit by drought [14]. Despite the success of water market initiatives in areas such as the Murray–Darling Basin in Australia, they are not without critics. For example, in the state of Idaho, the population was slow to adopt the concept of water markets due to "high transactions costs, third party effects, and the persistence of historical institutions for water allocation [24]."

Many mechanisms for mitigating drought through infrastructure and pricing exist, such as optioning water rights or adapting water pricing, but water markets offer particular promise. They can be put into place quickly or established on a more permanent basis. Short-term water markets and similar mechanisms are more readily adopted by farmers and boast of an impressive track record at preventing economic losses in drought-prone, agriculture-dependent regions [14,24,31,46].

2.6 Planning for and Mitigating Drought

Globally, agricultural irrigation uses some 70% of all freshwater consumed and a much higher ratio in arid countries or regions. Therefore, drought management must pay special attention to water consumption in the farming sector. Water demand management is water conservation achieved through boosting crop yields per unit of water. This requires a three-pronged approach:

1. *Technological responses*: Practicing drip irrigation and (solar) desalination, and using (solar) water pumps as well as water-efficient residential and commercial appliances. Such responses are appealing because they provide what is seen as a "drought-proof" water supply system.
2. *Behavior modification*: Raising awareness about the value and paucity of freshwater supplies and the need to conserve them.
3. *Institutional/governance responses*: Implementing transparent and inclusive decision-making processes, adjusting water supply, and changing pricing signals, among other factors.

The timeline for each of these approaches varies, some taking years to bear tangible results. Pre-drought planning is critical to the successful mitigation of the effects of this natural phenomenon. Absent that, governments are likely to respond to a drought through a crisis management lens, with all the shortcomings that entails. For example, environmental flow requirements will be given a very low priority and likely sacrificed. The proper analytical lens for drought mitigation is risk management.

2.6.1 Evaluating Drought Risk

Drought is a condition that strikes vast areas and can be difficult, but not impossible, to predict. Many regions around the globe are prone to drought. Prior droughts may serve as a reliable indicator of a region's propensity to experience this phenomenon, but the absence of historical droughts does not guarantee that an area is safe from drought.

A country's economic resilience can help to predict its stability following natural disasters such as drought. The less economically resilient a country is, the less likely it will have the necessary resources and mechanisms in place to support its population in times of severe drought, and the more likely it will be to experience political violence [44]. Some exceptions exist, however. Aid such as the Botswanan Drought Relief Program and related assistance to farmers through the country's Rapid Conflict Prevention Support program help to stabilize Botswana and prevent conflict during drought, although the success of that initiative may be the result of adaptation to repeated disasters of the same type [8].

The historical record is a good place to begin looking for signs that a region has drought potential. Just as certain regions in the world are more prone to tornados, others to earthquakes, and others to hurricanes, droughts tend to occur in specific regions. Drought prone areas are growing. Regions where drought occurred in the past are obviously prone to the phenomenon, but they are not the only place where a drought can happen.

Meteorologists and climatologists have created numerous models to examine natural climatological hazards around the globe. They have identified specific regions as being at high risk for drought, thanks to the use of paleontological climate data, existing weather conditions, recent trends, and other factors, including pollution and global drought patterns.

The strength, location, duration, and impacts of a drought are influenced by numerous factors. Mitigating the adverse effects of a drought phenomenon requires raising people's awareness, assessing needs, developing early warning systems, and crafting appropriate post-drought recovery plans. Drought-prone countries that plan for droughts' return (and not merely treat its onset as an emergency) will be best positioned to minimize droughts' impacts on its economy and quality of life. Building socially and economically resilient systems from the start is an effective way to deal with this natural hazard [15].

2.7 Summary and Conclusions

Unsustainable human utilization of natural resources is projected to aggravate the impacts of future droughts. It is found that, combined with the likelihood of a much drier future and increased water demand, the loss of groundwater and higher temperatures will likely exacerbate the impacts of future droughts, presenting a major adaptation challenge for managing ecological and anthropogenic water needs in the region. Although establishing early warning systems could help affected countries mitigate the impacts of droughts, the countries need to consider if their warnings reach all those who are at risk, including those who live in peripheral or remote areas, where the communication infrastructure may be poor or nonexistent. Another critical piece of the drought mitigation puzzle involves ensuring that the target population actually understands the risks and warnings that are being communicated. Illiteracy among farmers is often much higher than the rest of the population and highest among female farmers.

While individuals, communities, private organizations, and government bodies can take different steps to mitigate the impact of drought on agriculture, their capability to carry out such measures varies immensely. Droughts tend to have the strongest impacts on poor, if not the poorest, countries—those whose economies are heavily dependent on the agricultural sector. Paradoxically, these countries tend to be the least able to manage the consequences of droughts, due to their poverty and weak governance systems.

It takes extreme events to push governments to take appropriate measures to preempt or mitigate the effects of natural hazards. In economically and scientifically advantaged democracies, drought mitigation policies will become a political and social priority only after people associated with the farming sector suffer the extended, harsh impacts of megadroughts. Since 2015, the State of California in the United States is in the grips of a severe, multiyear drought, the likes of which has not be been seen in hundreds of years. Despite this, politicians are resisting transformational policies.

Much of the existing agricultural and irrigation-related research and development takes place in wealthier, industrialized nations. This may not benefit poor countries because climatic conditions and biomes vary from one place to another. Even though the primary responses to droughts cover technological solutions, behavior modification, and governance changes, implementing these would be an uphill struggle, potentially at the cost of development goals. In developing countries, especially those that have authoritarian governments, there is a clear "urban bias" to the approach and outlook of political leaders; rural regions are geographically and politically peripheral, which means that appeasing powerful elites who reside in urban centers, especially in the capital city, carries bigger political dividends.

Of the aforementioned responses, technological ones (e.g., drip irrigation) can be deployed in a relatively short time, which can yield potentially timely results that drought-stricken farmers would welcome. Even this approach has its challenges: the cost of initial investment, human resources that are capable of using and maintaining the system, and the suitability of the technology to the physical terrain and to the social and climatic conditions.

In addition to technological responses, behavior modification and establishment of good governance are critical to long-term, sustainable water management for farming in times of drought. These two responses take some time to set up and begin to produce results years after their implementation date. Managing the impacts of droughts on the agricultural sector is a complex matter that requires a patient, multifaceted, and inclusive approach.

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3

Capacity Building and Drought Management

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Abstract Drought is a new challenge presenting natural calamities to modern civilized societies. Natural resources are the fundamental treasures of human life and are also the driving force for sustainable development and human civilization. Geographically, the surface land of the world is divided due to climatic and tectonic conditions. Human civilization, urban development, and agricultural cropping patterns are totally dependent on naval communication and water availability. The changing behavior or changing nature of climate and the scarcity of water and increase in temperature is creating annual droughts in different parts of the world. Soil formation and fertility development depend on the water supply and quality of surface and ground water storage. Due to climate change impacts such as droughts, cyclones, floods, and other natural calamities. It has been estimated that the similar characteristics appeared in the tropical and subtropical regions. It has also been indicated that by 2025, 1.8 billion people will be living in regions with absolute water scarcity and about two out of three people in the world could be living under considerations of water and natural resource stress. Therefore the sustainable use of natural resources including water, soil, forest, air, oil, gas, and petroleum in the mining sectors should be considered within terms of drought and other relevant environmental calamities. In such a crucial environmental situation, strategic drought mitigation policies and technological awareness is necessary to protect nature through mitigation and adaptation to drought and to reduce vulnerabilities to other natural calamities. The approaches are probable factors for drought mitigation and natural resources management in the vulnerable areas of the world could be considered as a priority basis environmental issue. Primary evaluation

indicates that an increased utilization of natural resources could be a threat to future food security and the sustainability of natural resources. The engineering technology setup of natural resources practices guideline is needed within the present drought and environmentally harsh conditions. The innovation of a climate-smart approach and a drought management plan could be practiced globally toward protecting of natural resources from drought damages through capacity buildings.

3.1 Introduction

The world population has gradually increased from 2 to 20 million, when agriculture was first established about 12 million years ago, today the population size is 7.2 billion in 2013. The present figure will reach 9.6 billion by 2050 and 11 billion by 2100 [80]. Consequently, global food production will have to be increased by 50% to meet the demand of the present population growth. Global natural resources play a potential role in food production, economic development, and the balance of natural ecology [23,80]. Particular interest has been shown to different categories of natural resources around the world with regard to the extent of their uniqueness and attributes [54]. This includes forest, wetlands, soil, vegetation, fisheries, livestock, water bodies, habitats, and wind and mineral resources. These resources are found in every continent except Antarctica and in very rough climates from the tropics to the tundra. The forest is the most important natural resources are frequently uses in different regions of the world. It is estimated that 31% of the world's surface area represents forest resources [23]. The most critical areas are the developing countries in Asia, Africa, and Latin America, where huge volumes of people are dependent on forest resources. A total of 750,000 km^2 of wetlands has been registered with the Convention on Wetlands of International Importance as of 2000 [54].

Forest and water resources in different regions of the world have great importance for a country's economic, industrial, ecological, socioeconomic, and cultural context [35] since they contain very rich components in the biodiversity of all valuable ecosystems [38,48,60].

The forest and wetland resources of developing countries, such as in Asia, Latin America, and African countries, have suffered drastically from the impact on natural resources of a growing human population and anthropogenic activities, climate change, and other natural calamities. Furthermore, natural resources are recognized as a factor in biodiversity conservation and in rural and urban socioeconomic improvement [3,60].

Drought is a natural disaster for society contrast climate change impacts as well as drought, cyclones, floods and other natural calamities are getting most critical environmental issues for analysis and discussion. Modern civilization, agricultural production, and technological development is totally dependent on green nature, natural resources, and water availability. All types of management are dependent on the proper planning of the sustainable use of natural resources and the establishment of good governance all over the world. This would be the right option to protect and conserve natural resources from the calamity of drought and other natural disasters [22].

In South Asia, in the Ganges-Brahmaputra-Meghna floodplain alone, approximately 2.1 million ha of wetlands have been lost due to flood control, drainage, and irrigation development [46]; therefore, wetlands are facing serious challenges from environmental changes and anthropogenic impacts [3,59,72]. Bangladesh is a land of wetlands; it lies in the eastern part of the Bengal Basin, one of the largest river flood plains in the world. The people of Bangladesh have long depended on the basin's three formidable rivers, the Padma (Ganges), the Jamuna (Brahmaputra), and the Meghna, as well as their numerous smaller tributaries and distributaries, for fresh water, transportation, fish, and for the floods that deposit fertile silt on their farmland each year [74]. In Bangladesh, where inland water bodies constitute nearly 50% of the total land area, wetlands are critical to economic development and environmental improvement. The total area of wetlands in Bangladesh is estimated to be 70,000–80,000 km^2 [5,46]. This includes rivers, estuaries, mangrove swamps, marshes (*haor)*, oxbow lakes (*baor*), natural water shade (*beels*), water storage reservoirs, fish ponds, and some other lands [28,30,40,45].

The major roles of a wetland are nutrient retention/removal, support for food chains, fisheries production, habitat for wildlife, recreation, natural heritage values, biomass production, water transport, biodiversity presentation, and micro-climate stabilization [28,41]. All these environmental sectors are now affected by climate change as well as drought calamities in different parts of the world. A comprehensive analysis of the various issues leads to natural resources degradation in different parts of the world, such as in Asia, Africa, Latin America, Europe, and Australia, and the very specific case location in Bangladesh. This comparative analysis utilized applied research findings on the natural resources in Bangladesh and some other examples. The smart use of natural resources can solve ecosystem problems on global surface areas and ensure food security and the sustainability of community livelihoods in different climatic regions through capacity building. Capacity building is the process of gaining technical, managerial, and instrumental knowledge and insight into the relations between socioeconomic structures, cultural standards, and the values of the societies concerned. It aims to increase the flexibility of institutions and society to adapt to the changing circumstances. Specifically, capacity building encompasses the countries' human, scientific, technological, organizational, institutional, and resource capabilities. Throughout this chapter present drought mitigation and adaptation possibilities will be investigated in the Bangladesh case as well as in other cases.

3.2 Aims and Objectives

The objective of this chapter is to understand the characteristics of natural drought calamities in general and the drought distribution pattern in the world and the interlinked drought impacts. We will also investigate drought impacts on environmental issues so as to promote the sustainable management of natural resources in the global context. Capacity building is one of the key components for those interested in fostering the effective implementation of policies regarding wetlands and world forest protection in the context of sustainable natural resource management. The following specific objectives of drought management through capacity buildings are as follows:

- A special investigation limited to the Bangladesh case with a comparison to other countries in a global context
- To measure the protective scenarios of water shade and wetlands, soil conditions, forest ecosystems, and their biodiversity
- To measure the major threats of drought and to provide guidance for the wise use of natural resources toward mitigating drought vulnerabilities
- To recommend capacity building for the future development of natural resources from the effects of drought in the global context owing to climate change impacts, especially in developing countries

3.3 Concept and Scientific Understanding of Drought

Drought refers to a considerable and prolonged lack of rainfall over a wide area that significantly affects agriculture, domestic water supply, and water dependent economic activities, which may lead to famine. Scientifically drought is defined by the nonavailability of rainfall, leading to a decrease in the base flow and surface flow of water bodies and the depletion of soil moisture [57]. Drought is a temporary and recurring meteorological event which originates from the lack of precipitation over an extended period of time [55] and is a normal part of climate often described as a natural hazard. Drought by itself does not trigger an emergency, but a long lasting drought becomes an emergency due to its severe impact on agriculture and the lives of the drought victims. It is directly and/or indirectly related to life and livelihoods, water quality, air pollution, and food security, which are the basic requirements of any form of life [1,10–12,18]. Drought is primarily considered as an agricultural phenomenon that refers to the conditions where plants are responsive to certain levels of moisture stress that affect both vegetable growth and the yield of crops. It occurs when the supply of moisture stored in the soil is insufficient to meet the optimum need of a particular type of crop [21].

As a consequence of the usual hydro-meteorological variability, drought occurs in the pre-monsoon season when the potential vapor transpiration (PET) is higher than the available moisture due to uncertainty in rainfall, while in the post-monsoon season it is due to a sudden increase in temperature coupled with the nonavailability of rainfall that causes a sharp rise in PET. The offset of drought is slow as it is influenced by climatic fluctuations over an extended period of time. The affected area is widespread. Drought causes are seen in soil degradation, loss of crops, loss of economic activities, starvation or malnutrition, biodiversity, the spread of diseases, and so on. Drought is not aridity or desertification. Aridity is a dominant feature of dry regions, which refers to permanent conditions of low average precipitation. Water destruction and degradation of land resources may lead to desertification of an area, which originally was not an arid region [9].

3.4 Climate Change and Drought Impacts on Nature

Climate change impact is now a globally important issue in society from different socio-political considerations. Drought may lead to desertification or aridity if it prevails for a prolonged period accompanied with destructive land use practices [57]. Based on Warren [85], drought occurs when the moisture supply is abnormally below average for a period of up to 2 years. The types of drought need to be distinguished in order to understand the causes and effects. The types of drought to be considered are meteorological, agricultural, seasonal, hydrological, socioeconomic, land use, and cultural issues. The natural resources that are linked within these potential factors are those affected due to drought and water scarcity. The major division of natural resources is water, soil, forest, mining, and air resources. All these factors are the elements of weather and ecosystems. These are now being affected by drought extension in different parts of the world as well as in Bangladesh [81,82].

3.4.1 Impacts on Natural Resources

Species extinction appeared to be occurring at an unrivalled rate during the early 1990s. The International Union of Nature Conservation (IUCN) reports suggest that 25% of mammalian species are threatened with extinction. Out of a total 4327 mammal species, 1096 are regarded as at risk, while 169 are classified as critically endangered [65]. The loss of species diversity has become a global problem and unintentional and intentional human modification of habitats is the main threat to species [16,65]. Phillips and Mighall (2000) explained and stated that if the trends are not reversed, up to 50% of the world's species will become extinct over the next 50 years, with the annual estimated rate of extinction between 10,000 and 20,000 species [65].

Abramovitz [7] argues that human activities are creating a biodiversity deficit—by destroying species and habitats faster than they are being replaced with new ones—of 100–1000 times. All areas of human activity appear to be threatening biodiversity; commercial exploitation, illegal hunting and poaching, land use changes, and pollution all have direct or indirect effects [31,50,69]. Abramovitz also suggested that whole ecosystems are under threat, and reducing their size and integrity inhibits nature's capacity to evolve and create new life. The tropical reef ecosystems are diminishing as a result of habitat-destructive fishing techniques and mining that adversely affect all trophic levels. Furthermore, wetlands and mangrove cover are dwindling as they are reclaimed for agricultural and residential use, are submerged by dam/barrage schemes, or are used as rubbish dumps or for aquaculture [2,65]. In such conditions, the 1973 Endangered Species Act works on the very ecocentric principle that all life-forms may prove to be valuable sometime in the future and therefore each is entitled to exist for its own sake. Thus, the act contains power to protect any species that is considered, based on the results of scientific research, to be close to extinction, and 109 species were deemed to be either endangered or threatened in 1973; the number has since risen to over 900, with a further 3700 officially recognized candidates [51].

3.4.2 Impacts on Soil and Water Resources

Due to upstream fresh water extraction from river basins and sea level rise, temperature increase is also producing harmful soil and a degraded water environment in different parts of the coastal regions [39]. Drought is pushing endangered salmon in California to the brink. They were already endangered in the

Sacramento River, but the record drought parching of the western United States has brought the iconic fish even closer to extinction, as the king salmon needs very cold water for its eggs to develop. The present water salinity value in Bangladesh ranges from 54,025 to 69,152 dS/m and relates to an area that has been extended from south to north and east to west and which is extremely high, threatening the mangrove ecosystem services in the Sundarbans regions as well as in the whole Gorai catchment area [32,35,37]. Dry season salinity along the Nabaganga–Rupsha–Passur river system has largely been influenced by the dry season flow of the Gorai River. The trend of water salinity in the region is at an extremely high rate for agricultural crop cultivation and is even harmful for animals, fisheries, livestock, and agro-biodiversity [39]. As per an earlier soil investigation conducted by Soil Resource Development Institute (SRDI) in 1970, the soil salinity was mainly found in the Ganges tidal floodplain of the study area. The floodplain and the peat basins in the area were classified as a nonsaline zone where the soil salinity range was between 6001 dS/m to 8644 dS/m during the dry season (November–May) [32,39].

Since the withdrawal of water from the Ganges River there has also been extensive withdrawal of groundwater due to drought and agricultural irrigation; subsequently, saline groundwater and seawater from the south are intruding into the fresh water aquifers in the north. This salinization process is steadily overwhelming the local agro-ecological systems [39]. Therefore, the reduction of ecosystem services could be mainly attributed to the action of humans in the environment. A UN report stated that almost 50% of land had been highly degraded by anthropogenic influences [80,83]. The coastal land and wetlands are under pressure because the Asian coastal region contains more than 52% of the world's population [70]. By 2050, the number of countries facing water stress will rise to 18, affecting 600 million people. This future water stress and scarcity will have serious impacts on the socioeconomic improvement of the countries and will probably adversely affect their food production levels. It is likely that global warming and drought impact will affect the production of certain crops, such as rice, wheat, corn, beans, and potatoes, which are major food crops for many countries in Africa, Latin America, and the Asian continent [33]. The increase in temperature would be one of the root causes of a reduction of agricultural crop production. A case has been shown in Zimbabwe where the temperature has increased from 2°C to 4°C, which is changing the farming system and reducing the maize production rate; farmers need extra irrigation costs for agricultural production as soil fertility and water availability are becoming reduced [33].

3.4.3 Impacts on Mining and Mineral Resources

Global climate change is due to human-induced emissions of greenhouse gases, but local climate change is due to urbanization and land use change [43], which affects people's well-being through damages to their health [42]. Land use change affects the local climate by affecting the provision of ecosystem services (ES) [68]. The ecological, social, and economic impacts of climate are geographically unevenly distributed [53]. Mineral extraction and loss of traditional livelihoods are creating huge social problems and community migration, land use change, and occupational changes in different parts of the world. The more socio cultural occurrences are like displacement of people and settlement from mineral and mining regions, decline in access to natural resources, increase competition among local for resource uses and collection, and conflicts among farmers, stakeholders, and researchers. The Indian state of Orissa has achieved phenomenal economic growth largely from the mining and infrastructure sectors. The livelihoods of the large tribal population depends on natural resources, and due to stakeholders' pressure, drought impacts, and extreme weather events in the last decade, the traditional livelihood of people in Orissa has changed. The state is rich in mining and mineral resources, which are 24% coal, 17% iron ore, 98% chromates, 51% bauxite, and 35% manganese. There are 596 mining sites were leased with an area of 9,662.5 km^2, which contributes 7% to the state.

3.4.4 Landscapes and Land Use Changes

In this millennium, global drylands face a myriad of problems that present tough research, management, and policy challenges. The recent advances concerning sustainability, together with the integrative approaches of global change and sustainability science, suggest that concerns about land degradation, poverty, safeguarding biodiversity, and protecting the culture of 2.5 billion people can be confronted with renewed option. In many regions of the world, landscapes and land use are changing due to drought impacts and climatic harshness. The Sahel region is in sub-Saharan Africa, a transition zone between the tropical south and south central Africa and the Sahara desert, which are continuously changing their land use patterns [63,64]. The hyper-arid type of climatic condition is continuously moving southward due to climate change impacts such as drought. The Saharan region and other sub-Saharan countries share similar economic activities, namely, agriculture, forestry, livestock, and small agro-based industries [24,25]. Approximately 70% of the population of the sub-Saharan region depends on agriculture or related agricultural activities for their livelihoods. Today in the Sahel region, land use is changing to agricultural, with arable and pastoral farming providing an agro-ecosystem [44].

The region is experiencing a strong variation of climatic conditions with years of extreme dynamics (rainfall variations from 200 to 600 mm) and a reduction of rainfall leading to extreme droughts [9,13]. As landscapes and land use are continuously changing to agricultural farming only a few trees now exist on the Sahelian horizon, impacting both climate and anthropogenic disturbances. Figure 3.1 shows the consequences of land use changes that lead to degradation, dryness, and desertification in different geographical regions of the world. Natural land use changes very frequently in the Sahel region.

In Colombia, drought threatens one of the world's top coffee producers, the farmers of coffee beans located at 5900 ft on the slopes of the Galeras volcano. Nariño, in south-western Colombia, is certified as a top coffee producing region for its mellow-tasting, fine-smelling produce. More hours of sunlight means a higher concentration of sugar in the grain, but extreme weather is making it an ever greater challenge to keep producing the cherished beans for the world's cafes. But the recent water shortage is stressing farmers' coffee plants. Stalks have flowered and could yield a record crop, but they need more rain to do so. Reduced rain in South America in 2015 has caused a severe drought in Colombia. This type of drought could change the agro-landscape in Colombia as well as the microscale scenarios, as has been seen in other parts such as the Middle East and Asian countries. The north and north-west regions in Bangladesh are facing a serious scarcity of water and droughts which are appearing these days. The following model of land use change patterns is seen in the case areas in Bangladesh. In model (Figure 3.1) shows the land use changes due to extensive use of agricultural land, settlement development urbanization process in the rural Bangladesh as well as other parts of the world.

All these activities and climatic conditions have accelerated the totality of soil that is bare and open to wind erosion during the dry seasons [62,84]. The continuous reduction of topsoil through erosion due to poor conservation practices provides grounds for the reduction of vegetation cover and, when the soil

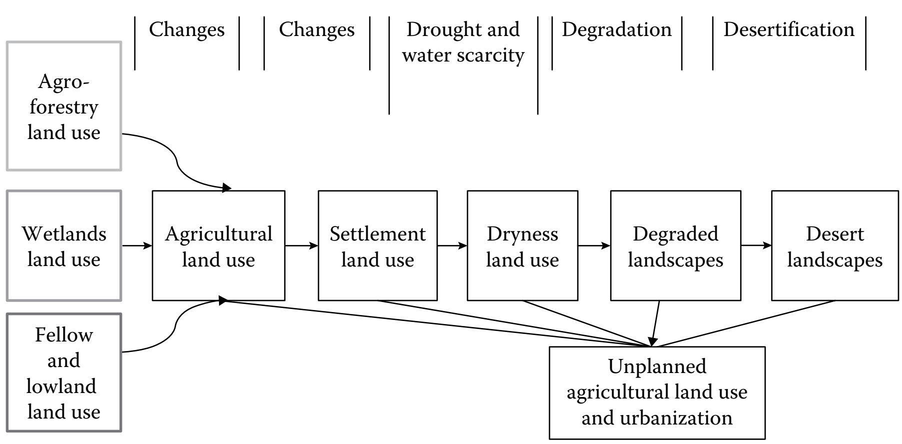

FIGURE 3.1 Consequences of land use change and degradation in the Sahel region of the African continent and other drought-prone and dry areas.

below the topsoil is compact, most of the rainfall water runs off into waterways [19,24]. The impacts of dryness and drought reduce vegetation cover that still go along with reduction of water recycling and monsoon circulation, thus a continuous decline in preparation of land use change and damage of agricultural crops production in the African Sahel and sub-Saharan regions.

3.4.5 World Forest and Vegetation Cover Changes

Forest is the most important and potential natural resource for world food security and economic and industrial development. Forest resources provide food and industrial raw materials as well as economic effects in the global market. Forest covers 4.03 billion ha globally, approximately 30% of the earth's total land area [23]. It accounts for 75% of terrestrial gross primary production and 80% of the earth's total plant biomass and contains more carbon in biomass and soils than is stored in the atmosphere. Almost 31% of the earth's total forest area is found in Asia (including Asian Russia), followed by 21% in South America, 17% in Africa, 17% in North and Central America, 9% in Europe, and 5% in Oceania [23].

Globally, 5% of forests are plantations, generally used for commercial purposes. Some 46% of the tropics (1.9 billion ha) is covered by forest and half of this can be reasonably termed rainforest (Table 3.1). This forest type—at its most dramatic it is a multilayered, dense, evergreen forest, 45 m or more tall, with a forest micro-climate quite distinct from that of non-forest areas—is characteristic of the equatorial regions of all the major continental areas and which, where climatic and edaphic conditions allow, extends to the boundaries with the temperate zones [86]. The consequences of tropical deforestation operate at global, regional, and local scales and include the following:

- Losses of plant and animal biodiversity as a result of habitat destruction and modification
- Changes in global carbon mobilization from soils and vegetation consequent on land use change and global climate change
- Soil erosion, disruption of nutrient cycles, and soil fertility
- Alterations to hydrological regimes and water quality and downstream sites [77]

Table 3.1 shows the tropical and subtropical rainforest scenarios of the world; four geographical regions are categorized [77]. Forests around the world are now subject to the risk of high rates of tree growth decline and increased mortality due to a combination of climatic warming and drought, notably in semiarid settings. Forest growth has declined since 1994 and in inner Asia has been confirmed to semiarid forests. Fire occurrence and insect/pathogen attacks have increased in tandem with the most recent (2007–2009) documented episode of tree mortality. If warming in inner Asian countries further increases then forest stress and trees mortality might drive the eventual regional loss of current semiarid forests. Climate warming and drought have affected tree growth in one of the world's most extensive zones of semiarid forests in inner Asia, a region where a lack of data limits our understanding of how climate change may impact forest resources in Asian, African, and Latin American countries. It is also important issue for consideration that how climate change affecting on the coastal

TABLE 3.1 Major Areas of Tropical Rainforest

Geographical Regions	Area (× 10^4 km^2)
Americas (Amazon–Orinoco; Pacific South, America–Central America; Atlantic Brazil)	4.0
Malaysia and extensions (Burma–Thailand–Indo-China)	2.5
Papua New Guinea, North Australia, Sri Lanka	1.8
Africa (Central–West Africa; Madagascar)	8.3

Source: Slaymaker, O. and Spencer, T., *Physical Geography and Global Environmental Change* (*Understanding Global Environmental Change*), Addison Wesley Longman Ltd, London, U.K., 1998, pp. 1–257.

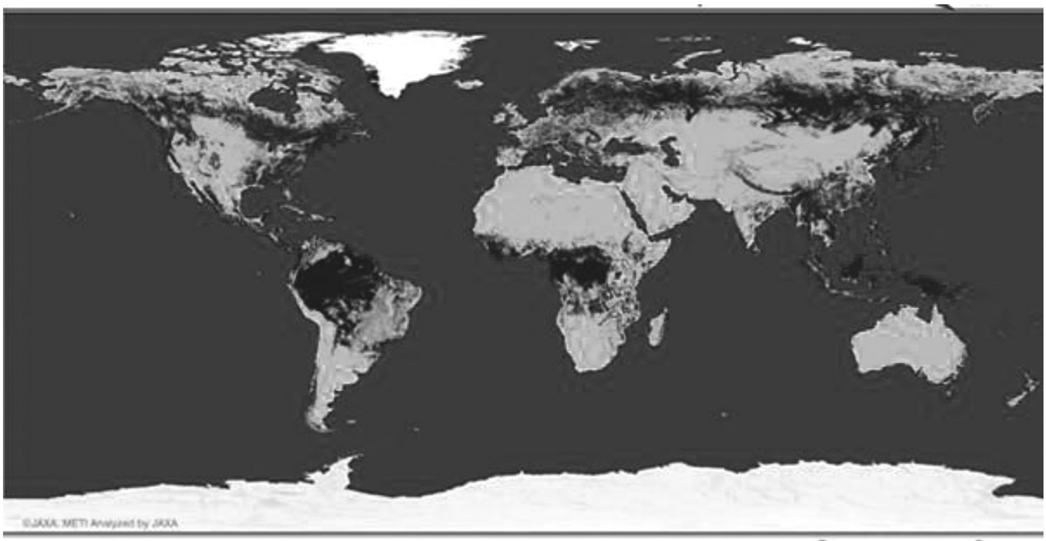

FIGURE 3.2 Distribution of world forest resources. (From JAXA, PALSAR 10 m Global Forest/Non-Forest Map, 2009.)

mangrove forest resources, since mangrove forest is very important for livelihoods in many Asian, African, and Latin American coastal communities [40].

The world's tropical and subtropical mangrove forest wetlands are found along tropical and subtropical coastlines, usually between 25°N and 25°S [72]. The world's mangroves predominate in Indonesia 24%, Brazil 7%, Australia 6%, Nigeria 6%, Cuba 4%, India 4%, Malaysia 4%, Bangladesh 4%, Papua New Guinea 3%, and Mexico 3%, with the rest of the world at 35% (Figure 3.2) [36,54]. Recent climatic impacts like high temperature and drought and dryness have manifested as large fires, such as the Rattlesnake Fire in the Coronado national forest (Arizona in United States) which is about 28,000 acres and the Coffee Pot Fire in Sandia national forest (New Mexico, United States) which is about 22,000 acres. These fires have drawn attention to the vulnerability of large numbers of communities. Similar forest fires frequently occurred in 2003 in Australia, Brazil, Russia, and Greece and in other parts of Europe, Latin America, and Caribbean countries.

3.4.6 Impacts on Global Wetland Resources

The world's wetlands play a potential role from an economic and ecological point of view. Particular interest has been shown to a number of wetlands around the world with regard to their extent, uniqueness, and attributes. This includes coastal and inland deltas, riverine wetlands, salt marshes and mangroves, freshwater marshes, and peat lands. They are found on every continent except Antarctica and in very rough climates from the tropics to the tundra. A total of 750,000 km^2 of wetlands were registered with the Convention on Wetlands of International Importance as of 2000 (Figure 3.2) [54]. According to the RAMSAR 1971 (The Convention on Wetlands of International Importance especially as Waterfowl Habitat) Convention, article 1.1, the term "wetland" links together a wide range of inland, coastal, and marine habitats, which share a number of common features [52,67]. Usually, wetlands occupy transitional zones between permanently wet and generally dry environments [20]. In Bangladesh, there are permanent wetlands and seasonal freshwater lakes and marshes of floodplains, which are known by different names: (1) *haor* (a bowl-shaped depression between the natural levees of a river mostly found in the eastern region of greater Mymensigh and Sylhet districts); (2) *baor* (an oxbow lake, being the dead arm of a river situated in the moribund delta of the Ganges); and (3) *beel* (the lowest part of the floodplain landscape, usually a saucer shaped wetland) [5,41,66].

Wetlands in different parts of the world have great significance for a country's economic, industrial, ecological, socioeconomic, and cultural context [35]. They contain very rich components of the biodiversity of a valuable ecosystem [48], which serves as a habitat for a variety of resident and migratory waterfowl and endangered and commercially important species of national and international interest [38,60]. Moreover, it supports a rich biodiversity of flora and fauna, which substantially contributes to socioeconomic improvement for millions of people living especially in rural areas. This livelihood sustainability provides opportunities for employment, food and nutrition, fuel, fodder, transportation, and irrigation [60]. The wetlands of developing countries such as in Asia, Latin America, and Africa have suffered drastically from the impacts of a burgeoning human population and anthropogenic activities on the wetlands. Yet, wetlands are recognized as a driving force for biodiversity conservation and rural socioeconomic improvement [4,60,61]. The smart use of wetlands can solve the ecosystem problems in floodplain areas.

In the south Asian Ganges–Brahmaputra–Meghna floodplains alone, approximately 2.1 million ha of wetlands have water resources that are essential to human development processes and to achieving the millennium development goals, which seek to alleviate extreme poverty and hunger and to ensure environmental sustainability. The regional hydrology and wetlands are affected by natural calamities, anthropogenic influences, and climate change impacts. Most parts of the tropical and subtropical regions face hydrologic and water scarcity problems. Recurring water-related natural hazards, such as floods, cyclones, droughts, and a decline in water availability, combined with deteriorating quality, have undermined the local health and livelihoods of millions worldwide especially in the developing countries. Therefore, wetlands also suffer from different types of disturbances and are gradually sinking due to agricultural farming, settlement extension, and urbanization activities in Asia, Africa, Latin America, and even in Europe (Figure 3.3) [4,59,72].

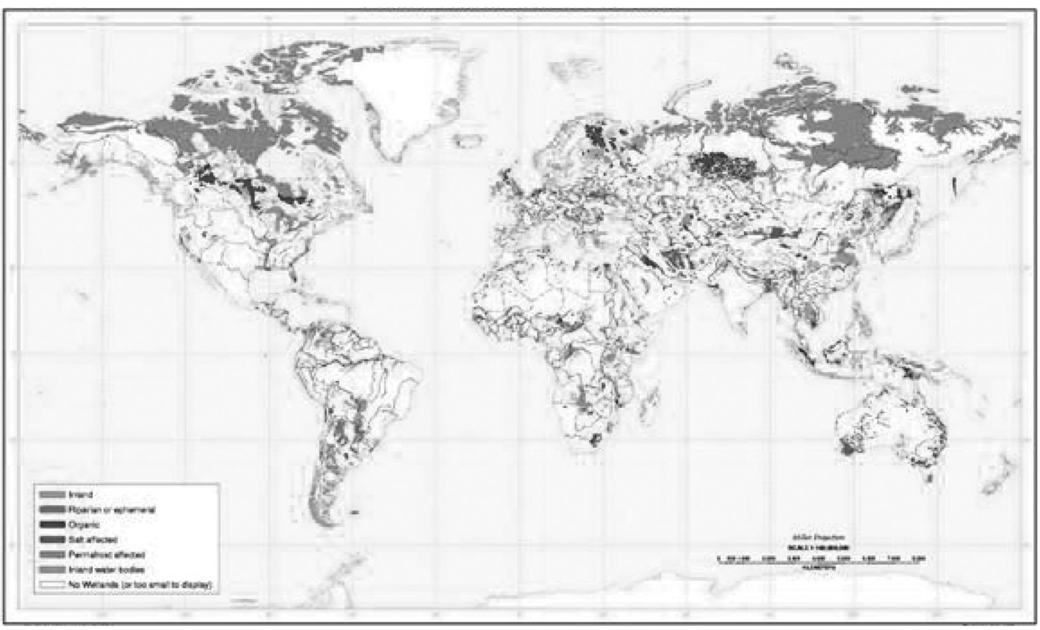

FIGURE 3.3 Distribution of global wetlands resources (including mangrove wetlands). (From U.S. Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS)-Global Distribution of Wetlands Map, USDA-NRCS, Soil Science Division, World Soil Resources, Washington, DC, 2003.)

There are thousands of wetlands distributed in different parts of the world, with the 10 greatest distributed across the different continents and across different climatic conditions:

1. Pantanal (Brazil) is the world's largest wetland, lying mostly in western Brazil but extending into Bolivia and Paraguay as well. It covers a region of 140,000 km^2.
2. The Sundarbans (Bangladesh and India) is the largest littoral mangrove wetland and covers an area of 10,000 km^2.
3. The Okavango Delta wetland (Botswana) is formed where the Okavango River empties into a basin in the Kalahari Desert and is 15,000 km^2.
4. The Everglades (Florida) covers an area of 512.4 km^2.
5. The Kerala Backwaters (India) extend for 590 km along the coast with the largest lake covering an area of 200 km^2.
6. The Kakadu wetlands (Australia) cover an area of 19,804 km^2.
7. The Mekong Delta wetlands (Vietnam) cover an area of 40,000 km^2.
8. The iSimangaliso Wetland Park (South Africa) covers an area of 3280 km^2.
9. The Wasur National Park (Indonesia) covers an area of 4138 km^2.
10. The Camargue wetlands encompass the Rhone River Delta in the south-east of France and cover an area of 1503 km^2 (Figure 3.3) [40].

In Bangladesh, the wetlands have suffered from an increase in the human population, and approximately 2.1 million ha have been lost to flood control, drainage, irrigation development, and other human developmental activities [60,61]. There are only 43 designated wetlands, and most of them are under threat from indiscriminate utilization, encroachment and reclamation, urbanization, agricultural development, and flood control. Almost 50% of the country's people are directly dependent on wetland resources [73]. The vast majority of poor people in wetland areas are dependent on their resources for their nourishment [38,40]. Therefore, a balance between the hydrologic water cycle and natural resource management plans and policies are needed to conserve these invaluable unique wetland sites [40].

Approximately 14 million ha of mangrove wetland areas are generally dominated by the red mangrove species (*Rhizophora*) and the black species (*Avicennia*) [54]. The present world mangrove vegetation cover has been estimated at an average of 17 million ha, of which half is in the Asia–Pacific region. The remaining 50% is equally distributed in Africa and America [33,40,49]. The modern approach to wetland construction is to include a potential role for socioeconomic improvement. In general, millions of industrially constructed wetlands have been used to treat wastewater or conventional water with different characteristics throughout the world every year, including domestic wastewater, various types of industrial wastewater, agricultural wastewater, and storm water.

3.4.7 Drought Impacts and Risk Analysis

The present trend of natural calamities and hazards, such as floods, droughts, rainfall, cyclones, earthquakes, and anthropogenic disturbances, are gradually increasing the vulnerabilities in different climatic regions of the world. Water scarcity and drought are the greatest challenges to maintaining food security and nutrition balance in communities. Some African countries are facing extremes of drought and dryness, which accelerate the negative slow speed of agricultural crop production and maintain the balance of ecosystem services and water supply for drinking and agricultural irrigation. The countries facing extreme drought problems include Somalia, the Democratic Republic of Congo, Haiti, Burundi, Chad, Ethiopia, Eritrea, Afghanistan, South Sudan, and Comoros. These countries are under extreme risk of a food and nutrition crisis. The following countries suffer from high drought, food security, and nutrition risk: Cambodia, Laos, Yemen, Iraq, Iran, India, Pakistan, Myanmar, Bangladesh, Libya, Sudan, Nigeria, and some other African countries. The following countries fall under a middle drought risk: Mexico, Brazil, Russia, China, and all countries of South America. The only few countries where

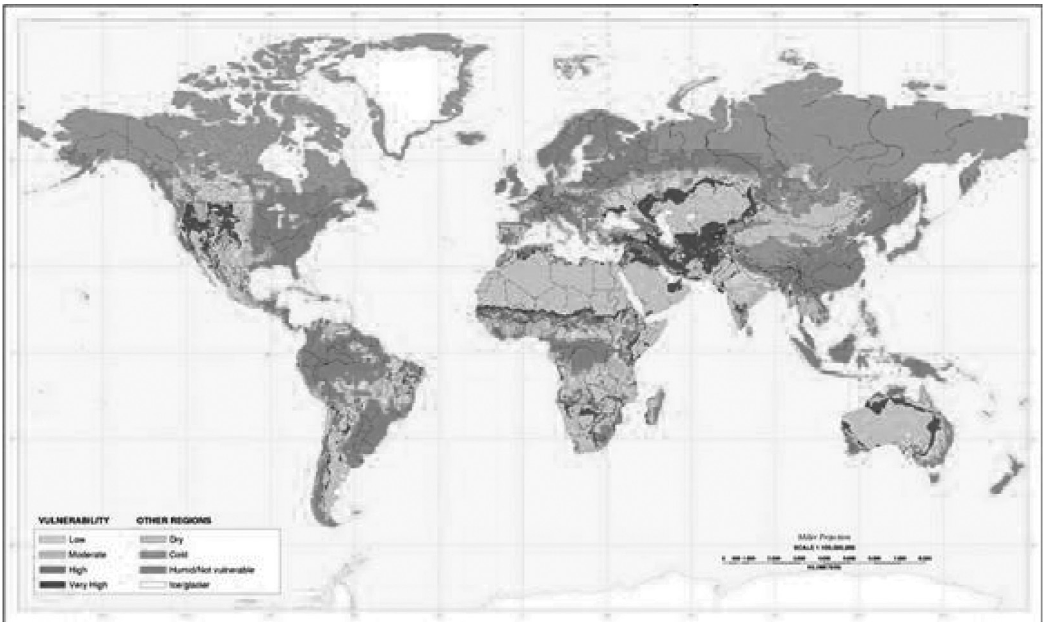

FIGURE 3.4 Global desertification vulnerability is imposing food insecurity. (From Soil Map and Soil Climate Map, USDA-NRCS, Soil Science Division, World Soil Resources, Washington, DC, 1998.)

there is no environmental or drought problem and which have food security include European Union members, the United States, Australia, New Zealand, Japan, and Chile.

The desertification vulnerability map (Figure 3.4) is based on a reclassification of the global soil climate map and global soil map.

3.4.8 Air Quality and Temperature Changes

Temperature change, air quality, and drought impacts are interlinked and in general are damaging the quality and quantity of natural resources. Particularly in the tropical and subtropical areas, agriculture is frequently seen as the antithesis of the natural world, where the problem is framed as one of minimizing land devoted to agriculture so as to devote more conservation of biodiversity and other ecosystem services. Surface agro-ecological practices have endured from time immemorial on a traditional basis. Temperature change, industrial gases, and climate change all impact agricultural lands and forest landscapes in different surface and coastal marine regions of the world.

The Intergovernmental Panel on Climate Change (IPCC) [33] has already estimated the scale of temperature change from 1901 through 2015, temperature rose at an average rate of 0.13°F per decade and the scale of the global sea-level rise has been assessed at 4 mm/year [33]. This temperature and sea-level rise is a new threat to natural resources, agricultural productivity, coastal urban life, and low-income community livelihoods and their health and life security. Traditional agro-ecological practices are so far poorly integrated in the actual agriculture systems of the world as there are so many climatic, anthropogenic, and industrial changes in play. The quality of the air, water, soil, temperature, and coastal marine ecosystem should be considered in relation to sustainable agriculture and industrial production–based planning. These agro-ecological practices have only a moderate potential to be broadly implemented in the next decade. By contrast, the following proposed future practices should be integrated: organic fertilization in agricultural production, biological pest control, afforestation programs to control the high temperature increase, and a sustainable manner of industrial development and urbanization planning.

3.4.9 Impacts on Fisheries and Livestock

Water resources in rivers all over the world supply fresh water for irrigation, fishing, and livestock development. In Bangladesh, major rivers are the main sources of fish. Fishing is important in Bangladesh but is not the main source of food or occupation, which is why this sector is not economically dominant. In Bangladesh, it has been estimated that 10,000 tons of fish were caught in the 12 months of 1993–1994, as a whole in that year of 1.09 million tons and government declared this figure of which 13% came from rivers and estuaries [17]. The river area in Bangladesh has been estimated at about 8400 km^2 for the total area of main river char lands, and at 2200 km^2 for the midland char lands, for 1980; the total area of fishing water is 67,000 km^2 [17]. The socioeconomic implications of fish culture as a livelihood source for communities living in char areas were also considered regarding their future development. The present status of Bangladesh as well as in other parts of the world is one facing a serious water scarcity problem to protect and conserve the water shade and water bodies for fish cultivation due to anthropogenic impacts to huge uses of natural resources and climate change impacts are most serious climatic barriers. The previous study findings on global scale has estimated that the economic value of ecosystem services lost through deforestation could be as high as USD2–4 trillion each year [26]. Many parts of the large river catchment areas are declining due to river erosion and natural calamities, especially in the coastal regions. Many of these types of extensive threats on grasslands which are used for cattle reared by local communities which products were met up the demand of the local and national demands for food security and nutritional demand fulfilling in tropical and subtropical regions as well as in South Asia and in Bangladesh.

3.4.10 Drought Impacts on Biodiversity and Ecosystem Services

Managing biodiversity in the face of natural calamities and anthropogenic disturbances is the most serious issue today. It is usual to think of biological diversity as more about plants, animals, and microorganisms and their ecosystems than about people and our need for food security, medicines, fresh air and water, shelter, and a clean and healthy environment in which to live. Maintaining the earth's biodiversity is essential for the natural environment to deliver the goods and services on which humanity thrives. It is furthermore a key dimension of poverty alleviation. Natural calamities, anthropogenic influences, and climate change impacts are now the major threats to biodiversity protection and keeping ecosystems friendly. The United Nations, the European Union, Asian nations, and the African community are now actively concerned with biodiversity conservation and the protection of ecosystem services. The European Union (EU) estimated that by 2020 the global comments made in Nagoya in Japan in October 2010 in the context of the Convention on Biological Diversity (CBD) its set of 20 global targets. Some regional political associations and environmental research institutions have already started to orient plans for the implementation of CBD target strategies. The EU has outlined six most important strategies which are targeted by 2020 actions and these are formulated for actions and among them two are very potential strategic actions are the maintenance and protection of agricultural and forestry ecosystems. Other important actions are to maintain and restore ecosystems and their services and to increase the contribution of agriculture and forestry to maintaining ecosystems and biodiversity [22].

Climate change impacts, such as floods, cyclones, tornadoes, salinity intrusion, dryness extension, water scarcity, and drought, are threatening biodiversity and ecosystem services. Most parts of the earth's surface are facing severe climatic and anthropogenic impacts. Habitat conservation and biodiversity loss, water scarcity and pollution, greenhouse gases, soil erosion and degradation are all relevant to agricultural crop production and community livelihoods in cold, tropical, and subtropical climatic regions [22].

3.5 Drought Impacts on Natural Resources: The Bangladesh Case

Drought is one of the most severe natural disasters in northern Bangladesh and causes immense suffering to people in various ways and threatens natural resource management [56]. In 1975, Bangladesh experienced a severe drought; 47% of the area and 53% of the population were affected. Monsoon rainfall, although very heavy compared to surrounding areas, suffers from extreme variability, often exceeding 60%. The lower the amount of rainfall, the higher the variability holds good in the north-western and south-western parts of the country [34]. Drought affects agricultural food production and human life in general in the north, but is gradually extending in a southerly direction [1,11,18,56]. The constructed wetland resources in Bangladesh can be seen on a very small scale [40]. Their management and regional hydrology is not in good shape worldwide, nor is it in Bangladesh [40]. A vast area of wetlands is lost due to flood control, drainage, and irrigation development—in Bangladesh as well as in other countries [46], hence forest and wetlands are facing serious challenges from environmental changes and anthropogenic impacts (Figure 3.5) [59,72].

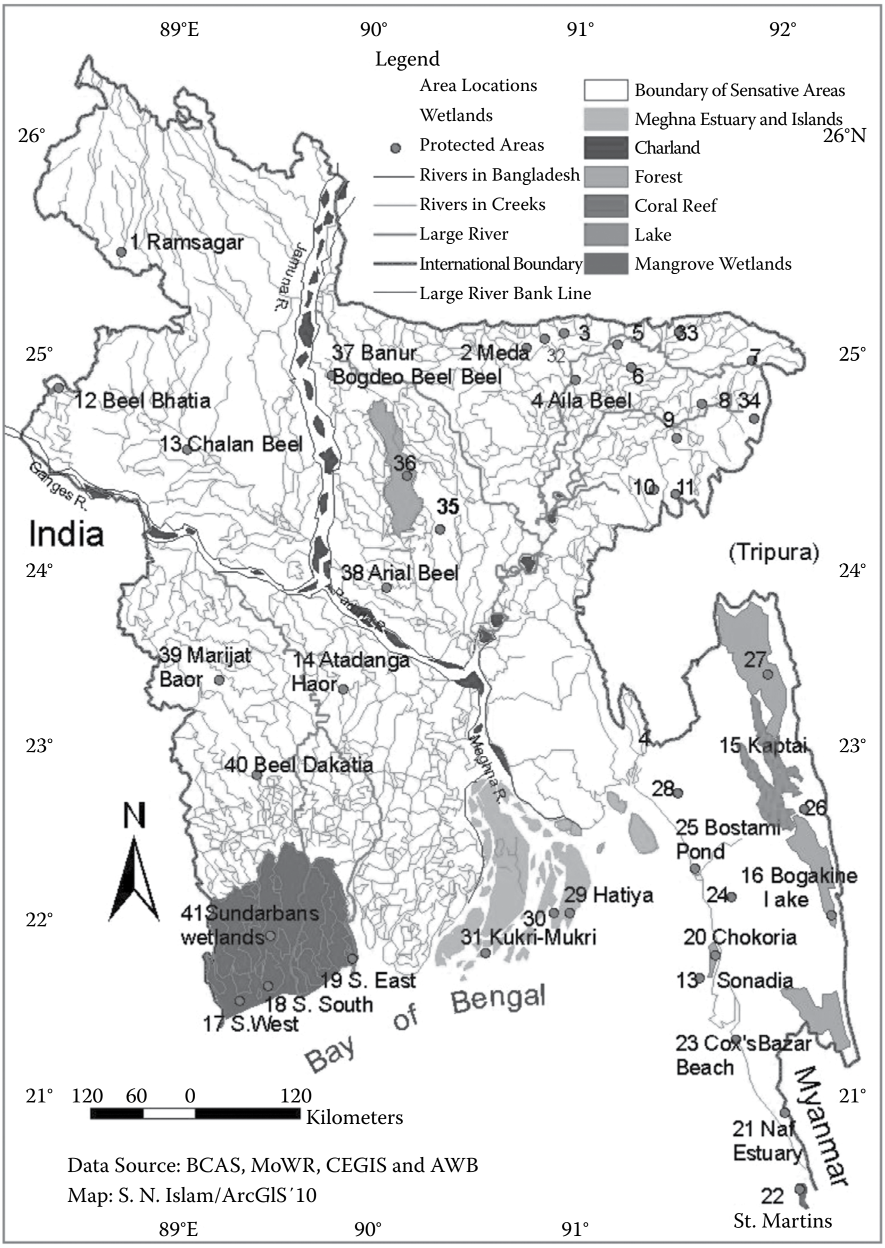

FIGURE 3.5 Forest and wetland distribution in Bangladesh. (From Islam, S.N., *Front. Earth Sci. China*, 4(4), 438, 2010.)

There are five types of wetland resource in Bangladesh: saltwater, freshwater, palustrine, lacustrine, and man-made. The important wetlands, forest patches, and river network patterns are shown in Figure 3.4. Presently, most of the wetlands in the country are under threat due to unsystematic utilization, encroachment and reclamation, urbanization, agricultural development, and flood control actions [27,46,60]. The protection and management status of wetlands in developing countries is more or less complex and severe due to financial, technical, social, and political decisions, as well as a lack of integration of those sectors [28,36,79]. The degradation of natural resources, especially land and forest, has become a subject of serious concern because the vast populations of these countries have to rely on these resources for their livelihoods [21]. Agroforestry, a land use system of growing different species of woody perennials in association with field crops, is a suitable system specifically for degraded areas. It helps to control soil erosion, hold back environmental degradation through the biological interactions of trees and crops, and increase income from farmland [29,47,71].

The land use system within agroforestry has been considered to be an effective and low-cost method as it does help to minimize the process of degradation associated with land cultivation and also for its retention of the ecosystem [8]. This method is widely used as a scientific instrument assuring food security, alleviating poverty, and enhancing ecosystem resilience with smallholders in the tropical and subtropical regions [47,76]. In Bangladesh, the total agricultural land use was about 1,000,370 km^2 (71.1%) in 1990 and was 940,000 km^2 (72.2%) in 2000. In general, the forest area was about 8,820 km^2 (6.8%) in 1990, 14,680 km^2 (11.3%) in 2000, and 1,440 km^2 (11.1%) in 2010. On the other hand, Bangladesh contains 1245 km^2 of inland moist deciduous Sal (*Shorea robusta*) forest, which is widely known as Vhawal—Madhupur Terrace and Sal Forest and extensively distributed in the districts of Dhaka, Gazipur, Tangail, and Mymenshingh, other patches of Sal forest are distributed in Comilla, Dinajpur, and Rangpur districts (Figure 3.4) [6]. In recent years, most of the Sal forests have been severely damaged by anthropogenic activities like illegitimate felling and infringement by the local people and the Garo tribe in the Madhupur area of Tangail district [6,47]. Through the community activities the agroforestry system has developed over there which is the new threat for the Sal forest conservation. The Sundarbans mangrove forest is located in the southern coastal area and covers 6000 km^2, but the recent sea-level rise and salinization process has affected the forest (Figure 3.4). Consequently, the entire coastal region of 47,000 km^2 has gradually been affected by a different degree of saline water, which is a threat to agricultural crop production as well as fishing and livestock rearing in the region. This is harmful to nutritional values, food security, and community livelihoods in coastal Bangladesh [6,40]. A comprehensive analysis of various issues leading to forest, soil, and water resource and wetland degradation in the Bangladesh case area has been analyzed (Figure 3.4). This comparative analysis of the different cases in different climatic regions has been carried out on Bangladesh as a model case through applied research findings on natural resources uses, management, and sustainability efforts [78].

3.6 Approach of Capacity Building and Drought Management Plans for Sustainable Usage of Resources

In global scale the natural resources are using abstractly according to the demand of the regional and national population. The present global population figure is over 7 billion in 2007 and is expected to increase to more than 9.1 billion in 2050. That means by 2050, 35% more food will be needed for the global population. Therefore, natural resources could be used more often without a sustainable plan. The amount of natural resources reduces due to large-scale use; and climatic impacts can be considered as a new threat to the conservation and management of natural resources. The triangle approach of utility and planning is illustrated in the model (Figure 3.5), which shows the uses of planning and future sustainability for natural resources.

Figure 3.5 shows the model where three triangle approaches are combined within the set of this following model. The triangle diagram model represents three potential subjects, such as ecology and ecosystem approach, socioeconomic and cultural aspects and productive usable aspects are three core issues which cover the environmental, economic, and productive issues. Based on these three topics, the natural resources could be used in a sustainable manner and wisely within the circular areas displayed in the inner site of the triangle approach of resource management. Through using this approach the future natural resource use could be possible within a development planning framework in all three climatic regions, such as the cold, tropical, and subtropical climatic regions in the world.

The concept and the findings of this study are illustrated that some recent initiatives have been undertaken by the Ministry of Environment and Forest, the Ministry of Land, and the Ministry of Water Resources of the Bangladesh Government. Most of the developing countries' the natural resources are not strictly controlled for conservation and management, as there are not enough laws or state legislation established. In general, natural resources such as soil, mining, forest, and fresh water are controlled by local elite groups and multinational companies. In such a process, international politics play a leading counterpart role in maintaining and controlling natural resources. Actions that are aimed at retaining natural resources have been undertaken to a lesser extent [40].

Climate change impacts such as drought, water scarcity, and salinization are more common features seen in the tropical and subtropical regions of the world. At the microscale, drought and water scarcity and salinization problems are recurrently affecting natural resources in Bangladesh which severely threatens environmental protection, health, and food security in the country. The rising groundwater level in wetland areas may increase evapotranspiration, and as a result there may be reduced runoff in the summer period. The freshwater wetland sites in the country are losing their hydrological cycle and scarcity of freshwater is creating ecological damage in different wetland sites all over the world as well as in Bangladesh. On the other hand, the mangrove wetland sites of the southern coastal region of Bangladesh are affected by saline water intrusion and degradation of water quality. The study result also reveals that the authorities do not follow any policy guideline or appropriate management approaches for natural resources conservation, either in Bangladesh or in most of the developing countries in Asia, Africa, and Latin America [39,58]. Figure 3.6 illustrates the model of natural resource use sustainability,

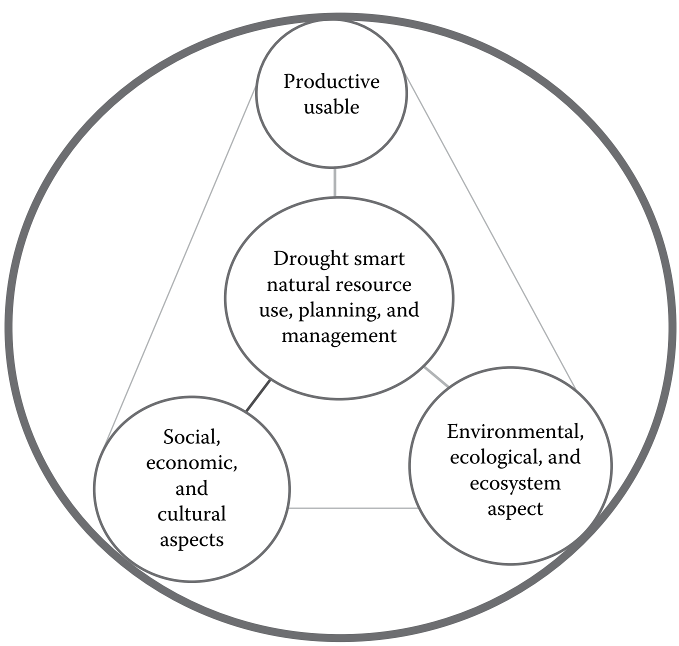

FIGURE 3.6 Natural resource utility, future development planning, and sustainability.

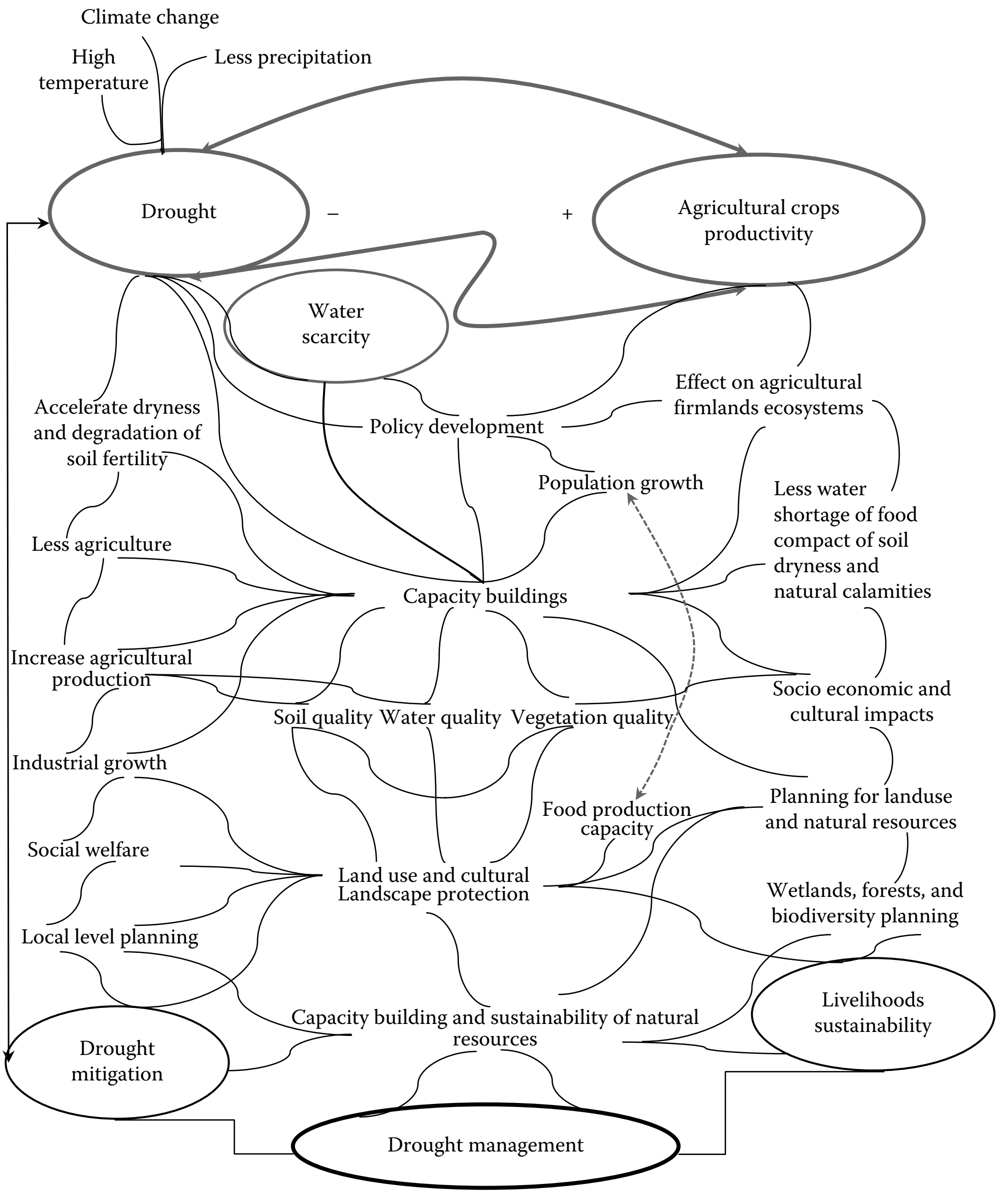

FIGURE 3.7 Model of drought mitigation and management through capacity building.

which could be extended with the conceptual model of Figure 3.7 and which could jointly ensure the use, conservation, and management sustainability of natural resources.

Considering the present management and conservation scenarios of natural resources due to climate change and environmental calamities and the study findings, the following natural resource management model (Figure 3.7) has been developed for proper implementation in the cold, subtropical, and tropical climatic regions where natural resources are strongly affected by drought and anthropogenic disturbances; however, the quality of human capacities is not developed based on climate impact issues [75].

In the model of natural resource management and use sustainability, the fundamental environmental factors and elements are closely interconnected and balance ecological and ecosystem functions (Figure 3.7), which are dependent and linked with other elements and factors and institutions

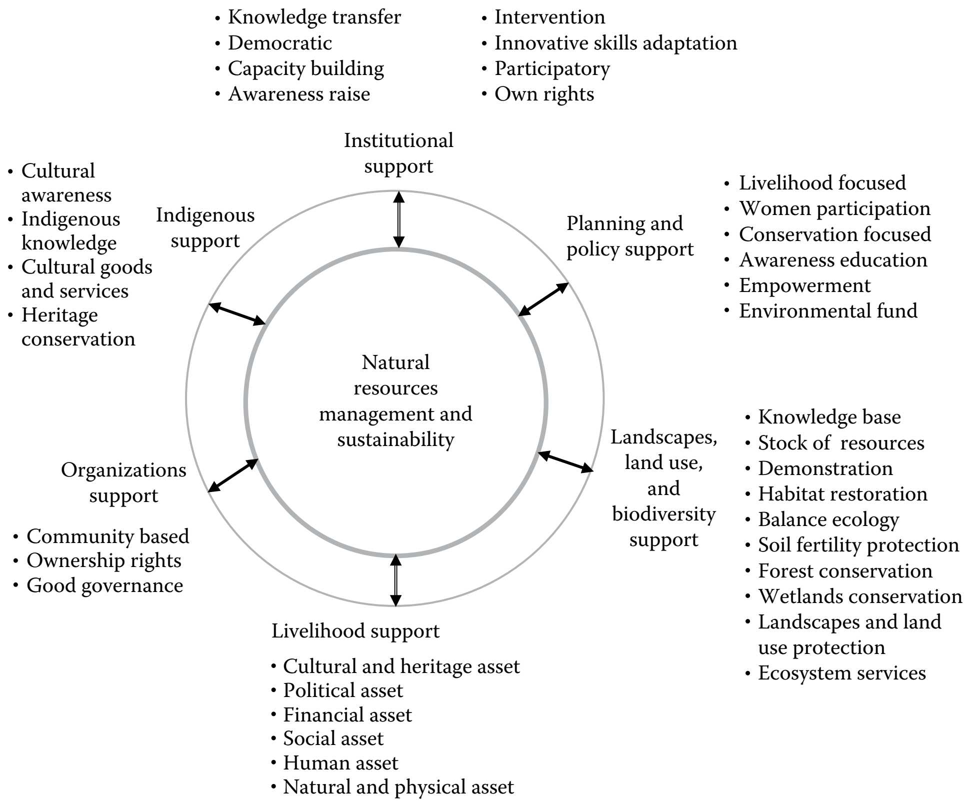

FIGURE 3.8 Model of natural resource management within drought hazards. (After Islam, S.N. et al., Wetland hydrology, in: Eslamian, S. (ed.), 2014. *Handbook of Engineering Hydrology*, Vol. 3: *Environmental Hydrology and Water Management*, Taylor & Francis, CRC Press, New York, 2014, Chapter 29, pp. 582–602.)

such as governance, population growth, the industrial estate, and urbanization process within the particular climatic region. The other potential factors include wetlands, water availability, soil quality, temperature, drought, forest patches, landscapes and land use, agricultural practices, biodiversity, ecosystem, and food security. All these elements, factors, and social, political, and economic aspects are interlinked for the protection and management and future sustainable use of natural resources (Figure 3.8).

Considering the climate change impacts and hostile environmental phenomena such as drought, floods, salinization, and natural calamities the fundamental elements of natural resource management and sustainability are adapted and illustrated in the conceptual model (Figure 3.8). The policy framework includes the following elements: (1) institutional support, (2) planning and policy support, (3) landscape, land use, and biodiversity support, (4) livelihood support, (5) organizational support, and (6) indigenous support [40].

The natural resource management situation and its ecological, socioeconomic, cultural, and environmental impacts are tragic in all climatic and geographical regions as well as in Bangladesh [35,41]. Natural resources have been used from time immemorial, but there have not been sufficient rules and regulations either in developed or developing countries. Some important national and regional laws and legislation were established in different countries in the twentieth century. The most well known are those in the United States, like the River and Harbors Act 1899, the Geothermal Stream Act 1970, the Clean Water Act 1972, the Geothermal Energy Research, Development and Demonstration Act 1974, the Safe Drinking

Water Act 1976, the National Environmental Policy Act 2005, and the National Environmental Protection Act 1969. In New Zealand, the Resource Management Act was declared in 1991. In Canada, the British Columbia Geothermal Resources Act was developed in 1973.

In Bangladesh after the UN Stockholm conference in 1972, the government initiated environmental programs for the first time with the creation of the Department of Pollution Control in 1974 and the enactment of the Pollution Control Ordinance in 1977. In 1989, the Ministry of Environment and Forestry was set up with the Department of Forests and a newly created Department of Environment under it. On April 13, 1992, the Draft Environmental Policy 1990 was approved by the Cabinet [34]. The National Water Policy was developed in 1999. The environmental policy statement describes six main objectives: (1) to help conserve and develop the ecological balance, (2) to save the country from natural catastrophes, (3) to identify the nature of all sorts of pollution and control, (4) to ensure durable development in a sphere suiting the demand of the environment, (5) to ensure judicious and long-term use of all national resources, and (6) to keep the nation alive to all international steps in connection with the environment as far as possible [34]. The National Wetland Policy also drafted in Bangladesh includes the following issues: maintenance of biodiversity and landscape protection, maintenance of ecosystem functions and ensuring socioeconomic benefits, and promotion of economic development and the establishment of principles for the utilization of sustainable resources [40].

For better planning and sustainable management of natural resources, the fundamental model, structure, and policy framework, and its prime factors and subfactors, should follow properly. The conceptual model (Figures 3.6 through 3.8) should be implemented in different climatic environmental locations as well as in Bangladesh and could achieve a good result for better management that could ensure livelihood sustainability for the communities and stakeholders who believe and would like to protect natural resources for future generations [14,15]. The findings of this chapter could become an important framework for planning and the sustainable management of natural resources and the conservation of ecologically sensitive sites in Bangladesh as well as in other parts of the world.

3.7 Summary and Conclusions

Natural resources are the most important driving force for socioeconomic and industrial development. They are the only source of food security and economic activity all over the world. Human resources and habitat and microorganisms are directly dependent on natural resources. The present rapid population growth and unplanned extraction of natural resources could be the future severe in-scarcity of natural resources that could be beyond of under control. Climate change impacts as well as drought are new threats to the control, management, and conservation of natural resources in cold, tropical, and subtropical climatic regions in the world. They have the ability to focus tremendous energy and to generate significant creative and economic betterment. In general, a country's wetland natural resources as well as its ecosystems become degraded due to anthropogenic influences and natural calamities.

Water scarcity and drought are creating imbalance of the hydrological cycle of wetlands, and forest regions are losing their balance to protect ecosystems in the particular case regions in Bangladesh and other similar regions of the world within the three different climatic conditions. Therefore, all these countries need adequate interdisciplinary policy, framework strategies and the political will to implement it for the sustainable management and protection of natural resources especially in the sensitive ecosystems regions like Bangladesh and other developing countries. The methods for the generation of transformative knowledge to achieve and maintain natural resources, agro-farming system development, fishing development, and in general the wise use of natural resources that could protect ecosystems, biodiversity in the cold, subtropical, and tropical climatic areas.

For any kind of research project, implementation that is harmful to the sensitive ecology in different climatic zones and political territories as well as in Bangladesh should follow the integrated strategies for sustainable natural resource protection.

The following issues are strongly recommended for the implementation on a global as well as a regional and national basis for the better management of natural resources:

- Increase public awareness concerning environmental monitoring, training, and education, particularly where related to the importance of the sustainable use of global natural resources for better achievement from ecosystem services.
- To provide information to the global, rural, and urban communities concerning potable drinking water and natural resources collection, properly uses for making balance of ecosystem services for long-term protection measures.
- Ensure community involvement in maintaining and protecting the quality, development, and management measures of global natural resources.
- Transfer technology and awareness knowledge to global, urban, and rural communities for the sustainable use of urban ecosystem goods and services in remote areas for socioeconomic and livelihood improvement and to ensure environmental sustainability.
- Continue environmental discourse and dialogue for understanding the importance and inevitability of capacity building skills to protect landscapes, land use, water, soil and forest resources, and their appropriate use within drought hazard conditions in different climatic regions.
- Develop and train up the capacity building of global communities, local governance, stakeholders, NGOs, national policy makers, and planners who are directly or indirectly involved in biodiversity conservation and natural resource management planning activities.
- Encourage technologies and special skills that restore ecosystems through entrepreneurs' investment in environmentally sound technology. Also improve the use of relevant information that can enhance and sustain the capacity to assess the consequences of ecosystem changes through productive data and information-based actions.
- Good governance should be the basic concern of capacity building and skills development, which could be used for natural resource allocation, protection, and management. The changes in institutional and environmental governance frameworks to enable effective management of ecosystems as such will ensure the sustainability of natural resource and protective management.
- Policy, principles, plans, a program for sustainable natural resource management, and specific guidelines should be more precise and concrete. The national natural resources management and use policies should be implemented properly; in addition a policy guideline of management issues should be incorporated in national resource policy in Bangladesh where it is necessary for the better management of ecosystems services and the improvement of the urban and rural socioeconomy. Therefore, an integrated global drought mitigation and adaptation policies and guideline framework should be prepared based on this study's findings and drought smart environmental planning is urgently needed for a sustainable natural resource development and protection of ecosystem services in Bangladesh and other climatic regions.

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4

Adaption to Droughts

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Abstract Droughts are one of the top three threats to the world population (along with famine and flooding). Drought is a complex phenomenon that is difficult to accurately describe because it is both spatially variant and context dependent. Although many definitions of drought exist, the central theme in the documented literature on drought is water deficiency. Drought primarily affects the agriculture, transportation, recreation and tourism, forestry, and energy sectors. Droughts are characterized by dry, cracked soils on riverbeds and lakes, dust, and parched plants and thirsty animals. Damage from droughts can exceed that resulting from any other natural hazard. All parts of our environment and our communities are affected by drought. The many different drought impacts can be grouped under economic, environmental, and social impacts. All of these impacts must be considered in planning corresponding to particular drought conditions.

Meteorological drought is usually defined by the measure of the departure of precipitation from the normal and the duration of the dry period. Agricultural definitions refer to situations in which the moisture in the soil is no longer sufficient to meet the needs of the crops growing in the area. Hydrological drought deals with surface and subsurface water supplies (such as stream flow, reservoir/lake levels, and groundwater). A socioeconomic drought occurs when economic goods associated with the elements of meteorological, agricultural, and hydrological drought fail to meet the demand.

Adaptation is adjustment to new or expected climatic conditions (and associated impacts) in order to minimize the damage that they cause or to exploit new opportunities that they bring. Adaptation takes place in both human and natural systems. It can be reactive and anticipatory, private and public, and planned and autonomous. Examples of adaptation to drought include farming different types of crops, harnessing water for irrigation, and migrating from rural to urban areas.

4.1 Introduction

Drought is a normal recurring event that affects the livelihoods of millions of people around the world, especially the 200 million people living in southern Africa. It is the most complex but least understood of all natural hazards, affecting more people than any other hazard in socioeconomic terms [23,24]. Drought differs from other natural hazards in several ways. First, the effects of droughts often accumulate slowly over a long period of time and may linger for years after the drought. Second, the onset and end of drought are difficult to determine, and because of this, drought is often referred to as a creeping hazard [16,23]. Third, despite its devastating impact, there is no precise and universally accepted definition of drought, and this adds to the confusion about whether drought exists, and if it does, about its extent and degree of severity. Fourth, drought has no structural and physical impact, which to some extent has hindered the development of accurate, effective, reliable, and timely estimates of its severity and, ultimately, the formulation of drought contingency plans by many governments in Africa [15,23,24].

Climate variability, which includes erratic and unpredictable seasonal rainfall, contributes to the risk of farming across most marginal rain-fed agricultural areas that are characterized by low and erratic precipitation. The latter situation is reflected in relatively low and notably unpredictable levels of crop and livestock production. A serious drought or a series of consecutive droughts can be a disaster-triggering agent that exacerbates social and economic problems and reduces the overall livelihood security of a society. These problems are most severe where economies are least diversified and virtually everyone depends either directly or indirectly on agriculture. Extended periods of drought or unusually high rainfall or flooding in these areas can have devastating effects on the already marginal levels of production, placing subsistence farming in jeopardy [26].

Drought conditions frequently require government intervention in the form of emergency food relief, often supported by large amounts of donated food aid. Drought preparedness by governments has generally taken the form of creating food reserves (mainly maize) at the national level to compensate for production shortfalls and provide for possible emergency relief. While these costly relief efforts have been perceived as a necessity, such short-term interventions have generally precluded support for longer-term development processes, particularly in those areas with dry climate conditions. As low and erratic precipitation is a key characteristic of these dryland areas, this fact of life must be reflected not only in the preparedness plans drawn up by governments but also in the longer-term development strategies designed to prevent serious impact of future droughts on the environment and people's livelihoods [26].

Increasing frequency and severity of droughts, the periodic shift in the onset of rains, and increasing intensity of midseason dry spells are major consequences of climate change. There are four types on drought: meteorological, agricultural, hydrological, and socioeconomic.

4.2 Types of Droughts

While the lack of water is the underlying cause of drought, a large number of other socioeconomic factors compound and intensify drought's effects. The absence of a precise and universally accepted definition of drought adds to the confusion about the occurrence and severity of a drought [23]. The various definitions of drought differ in their interpretation relative to their impacts and must be region and impact specific. Both natural and social components of drought need to be better understood and addressed in national, regional, and international policy planning. References [16,24] describe four basic categories or types of drought.

4.2.1 Meteorological Drought

Meteorological drought is a reduction in precipitation compared with a specified average condition over some specified period. It is defined as a period during which less than a certain amount (e.g., 70%) of the normal precipitation is received over any large area for an extended period. It is usually the type of drought referred to in news reports and the media [13]. Most locations around the world have their own meteorological definition of drought based on the average climate in the area. An area that gets less rain than usual can be considered to be experiencing a drought [16].

4.2.2 Agricultural Drought

Agricultural drought is a reduction in soil moisture below the optimal level required by a crop during each growth stage, resulting in impaired plant growth and reduced yield. Agricultural drought refers to an imbalance in the water content of the soil during the growing season, which although influenced by other variables such as the crop's water requirement, the soil's water-holding capacity, and the degree of evaporation, is also largely dependent upon rainfall amount and distribution. The agricultural industry faces challenges when an agricultural drought is experienced [23]. Shortages in precipitation, changes in evapotranspiration, and reduced groundwater levels can create stress and problems for crops.

4.2.3 Hydrological Drought

Hydrological drought is a reduction in precipitation falling on natural and artificial surfaces and subsurface water resources. It occurs when there is substantial deficit in surface runoff below normal conditions or when there is a depletion of groundwater supplies. Hydrological drought reduces the supply of water for irrigation, hydroelectric power generation, and other household and industrial uses. Many watersheds usually experience depleted amounts of available water because of this type of drought [24]. A lack of water in river systems and reservoirs can impact hydroelectric power companies, farmers, wildlife, and communities.

4.2.4 Socioeconomic Drought

This refers to direct and indirect impacts of drought on human activities. This relates to a meteorological anomaly or extreme event of intensity and/or duration outside the normal range of events taken into account by enterprises and public regulatory bodies in economic decision-making, thereby affecting production and the wider economy [23].

4.3 Causes of Droughts

As described earlier, a drought is a prolonged period of abnormally low rainfall, leading to a shortage of water. It is a period of dryness, which, especially when prolonged, causes extensive damage to crops or prevents their successful growth. However, operational definitions of droughts attempt to identify their beginning, end, impact, and degree of severity. If one knows when a drought begins, water conservation measures can be implemented by the time drought begins. Drought has many causes. It can be caused by very less or no rain or snowfall over a period of time. The causes of droughts are easily understood, but hard to prevent [13]. Depending on the location, crop failures, famine, high food prices, and deaths can occur. One of the scariest aspects of a drought is the onset time. Unlike other forms of severe weather or natural disasters, droughts often develop slowly and thus are hard to manage promptly.

Unlike a dry spell, a prolonged lack of rain will cause regions around the world to slowly dry out. Because of the slow onset of droughts, their cost is often only estimated. Droughts are one of the top three threats to the world population (along with famine and flooding). Sometimes, a drought takes decades to develop fully and thus predicting droughts is difficult. Droughts are completely natural, but their devastation can be far reaching and severe. Atmospheric conditions such as climate change, ocean temperatures, changes in jet streams, and changes in the local landscape are all causes of droughts [26].

One of the major causes of drought is climate change. Climate change is associated with the greenhouse effect. The greenhouse effect is a naturally occurring phenomenon necessary to sustain life on earth. In a greenhouse, solar radiation passes through a mostly transparent piece of glass or plastic and warms the inside air, surface, and plants. As temperatures increase inside the greenhouse, the interior radiates energy back to the outside and eventually a balance is reached. The earth is in a greenhouse and its atmosphere is the "piece of glass or plastic." Short-wave radiation from the sun passes through the earth's atmosphere. Some of this radiation is reflected back into space by the atmosphere, some is absorbed by the atmosphere, and some makes it to the earth's surface, which is later either reflected or absorbed. The earth, meanwhile, emits long-wave radiation outward. Gases within the atmosphere absorb some of this long-wave radiation and reradiate it back to the earth's surface. It is because of this greenhouse-like function of the atmosphere that the average global temperature of the earth is what it is, about 15°C [26].

4.4 Impacts of Droughts

Drought primarily affects the agriculture, transportation, recreation and tourism, forestry, and energy sectors. Droughts are characterized by dry, cracked soils on riverbeds and lakes, dust, and parched plants and thirsty animals. Damage from droughts can exceed that resulting from any other natural hazard. All parts of our environment and our communities are affected by drought. The many different drought impacts can be grouped under economic, environmental, and social impacts. All of these impacts must be considered in planning corresponding to particular drought conditions.

4.4.1 Primary and Secondary Impacts

Drought has primary and secondary (ripple) effects on a household or national economy. Primary or physical impacts include reduction in agricultural production, hydroelectric power generation, water-intensive nonagricultural production (processing), and domestic availability of water, which has health implications. Secondary impacts are those that affect gross domestic product (GDP); for example, reduction in industrial output may lead to inflation and layoff of labor, which increases unemployment [25]. These factors reduce demand, expenditure, savings, and GDP. Table 4.1 shows that the impacts associated with droughts are much more than simply a food supply problem, depending on the duration and severity of the drought.

Not all of the impacts listed in Table 4.1 occur with every drought, nor do droughts typically affect the entire region or country. However, almost every year, there is some subnational area that is affected by drought.

4.4.2 Country Economy Scenarios

The typology presented in Table 4.2 is useful in distinguishing four country economy scenarios in terms of drought impacts. Under this approach, South Africa is classified as a dual/extractive economy that consists of a rural economy with a high level of subsistence production as well as a developed urban manufacturing and service sector. Mozambique is classified as a country with a relatively simple economy, based primarily on agriculture. Botswana and Zimbabwe are classified as countries with an intermediate economic structure based on a combination of agriculture and manufacturing.

TABLE 4.1 Impacts of Drought

Primary Impacts	Secondary Impacts
Social	
Disrupted distribution of water resources	Migration and resettlement
Increased quest for water	Increased conflicts between water users
Marginal lands become unsustainable	Poverty and unemployment
Reduced grazing quality and crop yield	Overcrowding and reduced quality of life
Employment layoffs	Reduced or no income
Increased food insecurity	Malnutrition and famine, civil strife, and conflict
Increased pollutant concentrations	Public health risks
Inequitable drought relief	Social unrest and distrust
Increased forest and range fires	Increased threat to human and animal life
Increased urbanization	Social pressure and reduced safety
Environmental	
Increased damage to natural habitats	Loss of biodiversity
Reduced forest, crop, and range land productivity	Reduced income and food shortages
Reduced water levels	Lower accessibility of water
Reduced cloud cover	Plant scorching
Increased daytime temperature	Increased fire hazard
Increased evapotranspiration	Crop withering and death
More dust and sandstorms	Increased soil erosion and increased air pollution
Decreased soil productivity	Desertification and soil degradation (topsoil erosion)
Decreased water resources	Lack of water for feeding and drinking
Reduced water quality	More waterborne diseases
Economic	
Reduced business with retailers	Increased prices for farming commodities
Food and energy shortages	Drastic price increases; expensive imports/substitutes
Loss of crops for food and income	Increased expense of buying food and loss of income
Reduction of livestock quality	Sale of livestock at reduced market price
Water scarcity	Increased transport costs
Loss of jobs, income, and property	Deepening poverty; increased unemployment
Less income from tourism and recreation	Increased capital shortfall
Forced financial loans	Increased debt; increased credit risk for financial institutions

4.5 Drought Indices

The severity of drought can be identified by combining the various drought indices into a single index. Different indices have been not only proposed but also used for different purposes. Commonly used indices are listed in succeeding sections. It is useful for planners to track more than one index before making decisions because no index can be perfect for all situations.

4.5.1 Percent of Normal Indices

The percent of normal indices are well suited for the general public and weather casters. These can be easily calculated and can be associated and combined with any hydrological variables such as precipitation, rainfall, soil moisture, reservoir storage volume, or groundwater level. The easiest measurement of rainfall or snowfall for a catchment or location is the percent of normal indices based on precipitation. If these indices are used for a single region/catchment, then the analysis is more effective. The index value is 100 times the actual value divided by the average value (typically considered to be a 30-year mean). Normal for a specific location is considered to be 100%.

TABLE 4.2 Impacts of Drought on Different Economic Structures

Various Aspects of the Economy	Economic Structure			
	Simple	Intermediate	Complex	Dual/Extractive
Per-capita income	Low	Low/low-middle	High-middle/high	Low/middle/high
Main sector	Agriculture	Agriculture, manufacturing	Manufacturing, service	Manufacturing, service, agriculture
Importance and nature of agriculture sector	Mainly rain-fed, accounting for >20% of GDP and >70% of employment	Rain-fed/irrigated, accounting for >20% of GDP and 50% of employment	Mainly irrigated, accounting for <10% of GDP and <20% of employment	Rain-fed/irrigated, accounting for 10%–20% of GDP and 20%–50% of employment
Intersectoral linkages	Weak	Intensive	Diffused	Weak
Engine of growth	Agriculture	Agriculture/ nonagriculture	Nonagriculture	Extractive sector
Infrastructure	Limited	Extensive	Extensive	Limited/extensive
Spatial impact of drought	Largely rural, area directly affected	National, rural, and urban population	Largely rural, area directly affected	Rural
Economic recovery following drought	Relatively fast	Agriculture—relatively fast	Agriculture—relatively fast	Agriculture
		Manufacturing—more slowly	Manufacturing—no real impact	Limited knock-on affects

The percent of normal indices can be calculated for a variety of time scales ranging from a single month to a few months representing a particular season to an annual or water year. The hydrological values are random on monthly or seasonal scales and are generally not normally distributed. This is a disadvantage of using the percent of normal value as the mean/average is not the same as the median (the value exceeded 50% of the time in a long-term climate record).

4.5.2 Standardized Precipitation Index

The Standardized Precipitation Index (SPI) was developed primarily for defining and monitoring drought. It allows an analyst to determine the rarity of a drought at a given temporal resolution of interest for any rainfall station with historical data. Mathematically, the SPI is based on the cumulative probability of a given rainfall event occurring at a station [19]. The historical rainfall data of the station are fitted to a gamma distribution as the gamma distribution has been found to fit the precipitation distribution quite well. This is done through a process of maximum likelihood estimation of the gamma distribution parameters, α and β. In simple terms, the process allows the rainfall distribution at the station to be effectively represented by a mathematical cumulative probability function. Therefore, based on the historical rainfall data, an analyst can then calculate the probability of the rainfall being less than or equal to a certain amount. Thus, the probability of rainfall being less than or equal to the average rainfall for that area will be about 0.5, while the probability of rainfall being less than or equal to an amount much smaller than the

TABLE 4.3 Classification of SPI Values

2.0+	Extremely wet
1.5–1.99	Very wet
1.0–1.49	Moderately wet
−0.99 to +0.99	Near normal
−1 to −1.49	Moderately dry
−1.5 to −1.99	Severely dry
−2 and less	Extremely dry

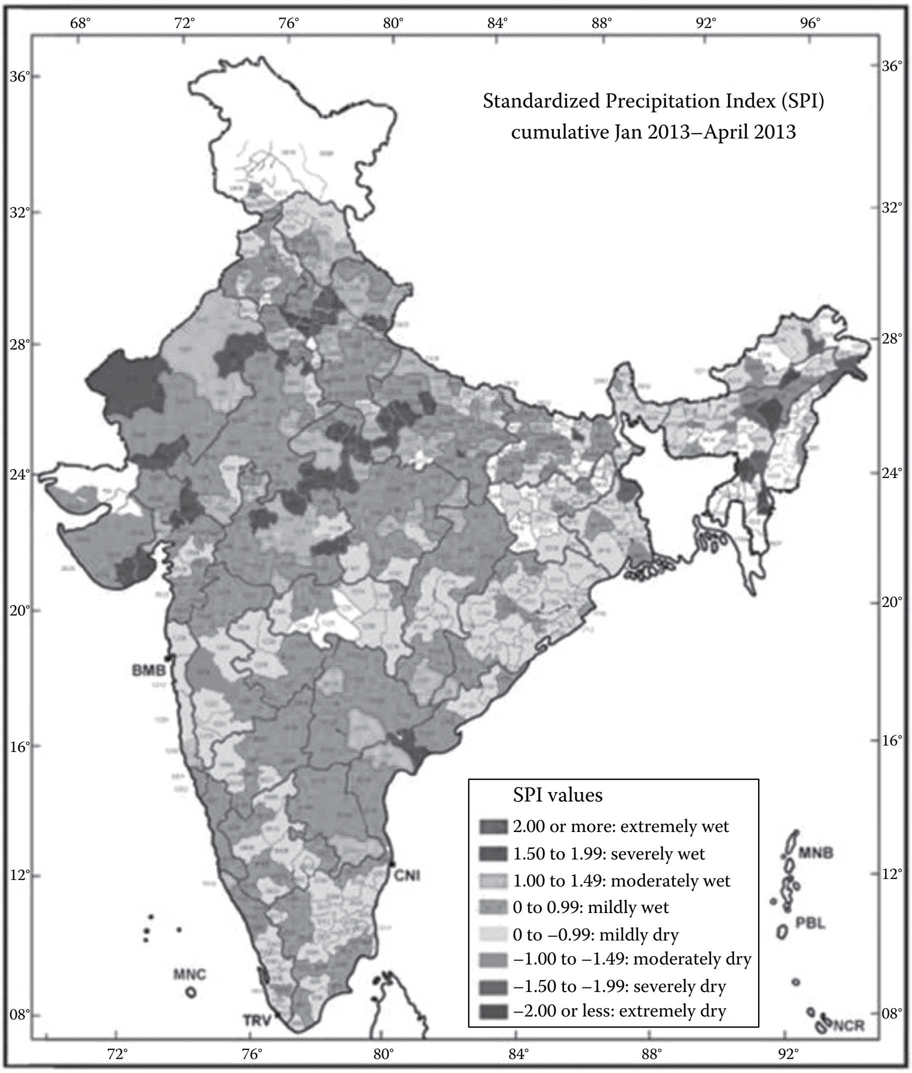

FIGURE 4.1 SPI map of India.

average will also be lower (0.2, 0.1, 0.01, etc., depending on the amount). Therefore, if a particular rainfall event gives a low probability on the cumulative probability function, then this is indicative of a likely drought event [19]. Alternatively, a rainfall event that gives a high probability on the cumulative probability function is an anomalously wet event. The classification system (derived using the SPI) presented in Table 4.3 can be used to define drought intensities.

Figure 4.1 presents the SPI values for Indian drought, published by the Indian Metrological Department.

4.5.3 Palmer Drought Severity Index

The Palmer Drought Severity Index (PDSI) attempts to measure the duration and intensity of long-term drought-inducing circulation patterns. Long-term drought is cumulative, so the intensity of drought during the current month is dependent on the current weather patterns plus the cumulative patterns of previous months. Since weather patterns can change from a long-term drought pattern to a long-term wet pattern, the PDSI (or PDI) can respond fairly rapidly. The PDSI is designed for relatively homogeneous regions, and the objective of the PDSI is to provide standardized measurements of moisture conditions so that comparisons using the index can be made between locations and between months. The PDSI responds to weather conditions that are abnormally dry or abnormally wet. It is calculated using precipitation and temperature data. Also, the local available water content (AWC) of the soil is used in the calculation. Stream flow, lake and reservoir levels, or other longer-term hydrological variable values and irrigation data that indeed may still show a drought are not considered by this index [16].

Palmer developed the PDSI to include the duration of a dry or wet spell period. An abnormally wet month in the middle of a long-term drought should not have a major impact on the index, and a series of months with near-normal precipitation following a serious drought does not mean that the drought is over. Therefore, Palmer developed criteria for determining when a drought or a wet spell begins and ends [1,17]. In near-real time, the PDSI is no longer a meteorological index but a hydrological one, hence referred to as the Palmer Hydrological Drought Index (PHDI). The PHDI is based on moisture inflow or precipitation, outflow, and storage. It does not take into account the long-term trend [16].

The PDSI varies between −6.0 and +6.0. Palmer arbitrarily selected the classification scale of moisture conditions, shown in Table 4.2, on the basis of his original study areas in the central United States [16]. Ideally, the PDSI is designed so that a −4.0 in one region has the same meaning in terms of the moisture departure from a climatological normal as a +4.0 in another region [1]. Table 4.4 shows the Palmer classification.

The PDSI has been widely used for a variety of applications and is most effective in measuring impacts sensitive to soil moisture conditions, such as on agriculture. It has also been useful as a drought monitoring tool and has been used to trigger actions associated with drought contingency plans. The capabilities of the PDSI that contribute to its popularity are that it provides decision-makers with a measurement of the abnormality of the recent weather for a region, it provides an opportunity to place current conditions in a historical perspective, and it provides spatial and temporal representations of historical droughts.

4.5.4 Crop Moisture Index

The Crop Moisture Index (CMI) was designed to evaluate short-term moisture conditions across major crop-producing regions, unlike the PDSI, which monitors long-term meteorological wet and dry spells. Moisture supply is reflected in the short term across major crop-producing regions, and the index is not intended to assess long-term droughts.

A meteorological approach is used to monitor the week-to-week crop conditions. It is based on the mean temperature and the total precipitation for each week within a climate division, as well as the CMI value from the previous week. The index responds rapidly to changing conditions. It is weighted by location and time so that maps, which commonly display the weekly CMI across a region, can be used to compare moisture conditions at different locations.

4.5.5 Surface Water Supply Index

The Surface Water Supply Index (SWSI) was designed to complement the PDSI for moisture conditions by Shafer and Dezman [20]. Though the PDSI is basically a soil moisture algorithm calibrated for relatively homogeneous regions, it is not designed for large topographic variations across a region. It does not account for snow accumulation and subsequent runoff. The SWSI is an indicator of surface water conditions in which mountain snowpack is a major component. The objective of the SWSI was to incorporate both hydrological and climatological features into a single index value [7]. This resembles the PDSI for each major river basin in the state of Colorado [20]. The values would be standardized to allow comparisons between basins. Four inputs are required within the SWSI: snowpack, stream flow, precipitation, and reservoir storage. Because it is dependent on the season, the SWSI is computed with only snowpack, precipitation, and reservoir storage in the winter. During the summer months, stream flow replaces snowpack as a component within the SWSI equation.

TABLE 4.4 Palmer Classification

4.0 or more	Extremely wet
3–3.99	Very wet
2.0–2.99	Moderately wet
1.0–1.99	Slightly wet
0.5–0.99	Incipient wet spell
0.49 to −0.49	Near normal
−0.5 to −0.99	Incipient dry spell
−1.0 to −1.99	Mild drought
−2.0 to −2.99	Moderate drought
−3.0 to −3.99	Severe drought
−4.0 or less	Extreme drought

Monthly data are collected and summed for all the precipitation stations, reservoirs, and snowpack/stream flow measuring stations over the basin to determine the SWSI. Each summed component is normalized using a frequency analysis gathered from a long-term data set. The probability of nonexceedence, the probability that subsequent sums of that component will not be greater than the current sum, is determined for each component based on the frequency analysis. This allows comparisons of the probabilities to be made between the components. Each component has been assigned a weight depending on its typical contribution to the surface water within that basin, and these weighted components are summed to determine an SWSI value representing the entire basin. Like the PDSI, the SWSI is centered on zero and has a range between −4.2 and 4.2.

4.5.6 Reclamation Drought Index

The Reclamation Drought Index (RDI) is calculated at the river basin level. It incorporates temperature as well as precipitation, snow pack, stream flow, and reservoir levels as inputs. By including a temperature component, it also accounts for evaporation. The U.S. Bureau of Reclamation uses RDI as a trigger to release drought emergency relief funds. The RDI was developed as a tool for defining drought severity and duration and for predicting the onset and end of periods of drought. The impetus to devise the RDI came from the Reclamation States Drought Assistance Act of 1988, which allows states to seek assistance from the Bureau of Reclamation to mitigate the effects of drought. The RDI classification is listed in Table 4.5.

The difference between the RDI and the SWSI is that the RDI builds a temperature-based demand component and duration into the index. The RDI is adaptable to each particular region, and its main strength is its ability to account for both climate and water supply factors.

4.5.7 Deciles

Arranging monthly precipitation data into deciles is another drought-monitoring technique. It was developed by Gibbs and Maher [10] to avoid some of the weaknesses within the "percent of normal" approach. The technique developed divided the distribution of occurrences over a long-term precipitation record into tenths of the distribution. Gibbs and Maher called each of these categories a decile. The first decile is the rainfall

TABLE 4.5 RDI Classification

4.0 or more	Extremely wet
1.5–4.0	Moderately wet
1–1.5	Normal to mild wetness
0 to −1.5	Normal to mild drought
−1.5 to −4.0	Moderate drought
−4.0 or less	Extreme drought

TABLE 4.6 Deciles Classification

Deciles 1–2: Lowest 20%	Much below normal
Deciles 3–4: Next lowest 20%	Below normal
Deciles 5–6: Middle 20%	Near normal
Deciles 7–8: Next highest 20%	Above normal
Deciles 9–10: Highest 20%	Much above normal

amount not exceeded by the lowest 10% of the precipitation occurrences. The second decile is the precipitation amount not exceeded by the lowest 20% of the occurrences. These deciles continue until the rainfall amount identified by the 10th decile is the largest precipitation amount within the long-term record. By definition, the fifth decile is the median, and it is the precipitation amount not exceeded by 50% of the occurrences over the period of record. The deciles are classified into five groups. The classification is given in Table 4.6.

The decile method was selected as the meteorological measurement of drought within the Australian Drought Watch System because it is relatively simple to calculate and requires less data and fewer assumptions than the PDSI [21]. In this system, farmers and ranchers can only request government assistance if the drought is shown to be an event that occurs only once in 20–25 years (deciles 1 and 2 over a 100-year record) and has lasted longer than 12 months [22]. This uniformity in drought classifications, unlike a system based on the percent of normal precipitation, has assisted Australian authorities in determining appropriate drought responses. One disadvantage of the decile system is that a long climatological record is needed to calculate the deciles accurately.

4.

The method of truncation uses historical records of stream flow, precipitation, groundwater drawdown, lake elevation, and temperature [4]. The historical data have to be sorted in ascending order, and trigger levels are determined from the truncation level specified. For example, if stage 1 drought is defined as the 70% level, this corresponds to stream flows that are less than 70% of all flows. When using this method, drought events of higher severity are "nested" inside drought events of lower severity; that is to say, a 90% drought implies the occurrence of a 70% and an 80% drought (if those are the trigger levels selected). The highest level of severity determines the decisions to make.

4.5.9 Water Availability Index

The Water Availability Index (WAI) relates current water availability to historical availability during periods of drought by measuring the deviation-from-normal rainfall over the prior 4 months [5]. The WAI is multiplied by a constant to make the index fall between 0 and 10, with zero representing normal conditions and 10 a severe drought. Factors for minimum and maximum desirable reservoir pool elevation and stored volume and drainage area are included to account for multiple reservoirs within one watershed [11].

4.5.10 Days of Supply Remaining

The Days of Supply Remaining (DSR) Index includes current reservoir storage, forecasts future inflows from precipitation and snowmelt, and predicts demands for municipal supply and in stream flows [9]. It provides an objective and easily understood measure of the supply of water. As new sources of supply or new demands are found, the index remains applicable. The DSR is calculated by predicting future inflows and demands, and determining when the inflows and existing supply will no longer be adequate to meet demands. Table 4.7 shows how the DSR is calculated.

A simplified example shown in Table 4.7 illustrates this calculation. The DSR values are calculated at the beginning of each time step, for example, a week. At that time, forecasts are made of the subsequent

TABLE 4.7 Calculation of DSR Index Values Based on Weekly Time Steps and Forecast Inflow and Demands

Week	Beginning Storage Volume	Inflow Volume per Week	Demand Volume per Week	Ending Storage Volume	Demand Meet	DSR Days
Begin	100	100	120	100		7
+1	80	40	20	−10		14
+2	40	60	20	20		21
+3	0	20	10	60		28
+4	40	40	40	40		35
+5	40	40	40	40		42
+6	100	120	100	80	No	
+7	40	20	−10	10		

Source: Fisher, S.M. and Palmer, R.N., *Water Resourc. Update*, 3(108), 14, 1997.

weeks' inflows and demands. Inflows are added and demands are subtracted for each successive week until the remaining supply is less than the demand. In the example shown in Table 4.7, there are 100 units of storage currently available. Forecasts show that the projected demand cannot be met after 6 weeks from the present. There is adequate supply for the current week plus the following 5 weeks. Thus, only 42 days of supply remains. A water management agency presented with the data in this example could implement restrictions to try to reduce demand by 5%. If successful, that would maintain adequate levels of storage until the expected reservoir refill begins in 7 weeks. Alternatively, a new supply source could be sought, or other demand and supply management options could be analyzed. Determining just what actions one should take (given the uncertainty of supply and demand forecasts) can be based, in part, on such analyses, including simulations of alternative actions, given supply and demand situations experienced in the past [18]. Determining in advance what actions are appropriate under what specific conditions or values of the DSR and getting them accepted makes drought management substantially easier when under the stress of an actual drought. The particular values of the DSR or any other index values that trigger management decisions are called drought triggers. Figure 4.2 shows the cumulative SPI for India from June 2012 to April 2013.

There are three important concepts related to any disaster (e.g., drought), its impact, and the responses of natural and human systems. These concepts are highlighted in the following sections.

4.6 Vulnerability

Vulnerability is the degree to which a system is susceptible to or unable to cope with the adverse effects of an event, including climate variability and extremes. With regard to drought, vulnerability to drought is defined as economic, social, and environmental characteristics and practices of the country's population that make it susceptible to the effects of a drought. Vulnerability is reduced by the ability to effectively plan for, anticipate, cope with, and recover from droughts. Thus, vulnerability to drought is likely to change, either increase or decrease in response to changes in these social factors. It is, therefore, logical to assume that subsequent droughts in an area will have different effects, even if they are identical in intensity, duration, and spatial characteristics because societal characteristics will have changed. Vulnerability is also a dynamic process; thus, to assess it, one must possess a good knowledge of the current situation, the evolution and trends of the problems faced by the vulnerable, and the resources and choices that may be available to stakeholders in the future, including vulnerable groups. Vulnerability is the net effect of sensitivity and exposure on adaptive capacity. Mathematically, this can be denoted as

$$\text{Vulnerability} = f\left(\text{exposure, sensitivity, adaptive capacity}\right) \tag{4.1}$$

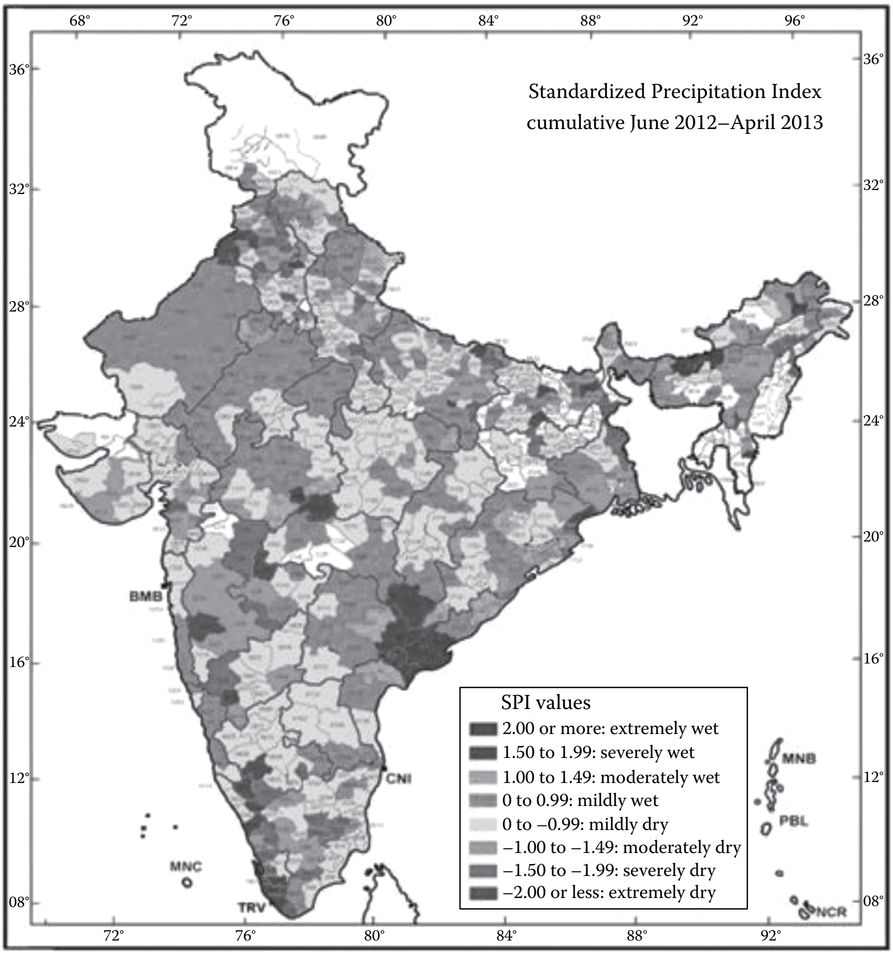

FIGURE 4.2 Cumulative Standardized Precipitation Index for India from June 2012 to April 2013.

With the three parameters (exposure, sensitivity, and adaptive capacity) mapped, vulnerability is then calculated simply as

$$\text{Vulnerability} = \text{Adaptive capacity} - (\text{sensitivity} + \text{exposure}) \tag{4.2}$$

In this relationship, a high (positive) net value indicates less vulnerability and vice versa. The greater the exposure or sensitivity, the greater is the vulnerability. However, adaptive capacity is inversely related to vulnerability. So, the greater the adaptive capacity, the lesser is the vulnerability [25]. Therefore, reducing vulnerability would involve reducing exposure through specific measures such as increasing adaptive capacity through activities that are closely aligned with development priorities. Figure 4.3 shows the impact of a hazard as a function of exposure and sensitivity. The chain sequence begins with the hazard, and the concept of vulnerability is noted implicitly, as represented by arrows.

As vulnerability to drought has increased globally, greater attention should be directed at reducing risks associated with its occurrence. This could be through the introduction of planning to improve operational capabilities such as climate and water supply monitoring and institutional capacity than just relief activities (Figure 4.4). Mitigating the effects of drought requires the application of all components of the disaster management cycle rather than the crisis management portion of the cycle [14]. Because of past

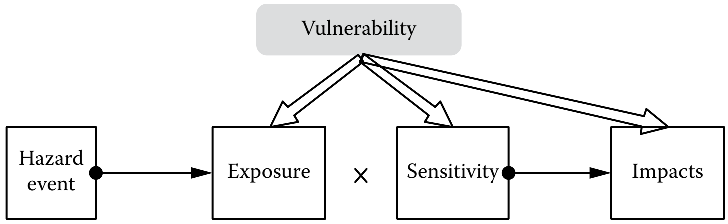

FIGURE 4.3 Illustration on the interplay of factors affecting the vulnerability of a system to drought.

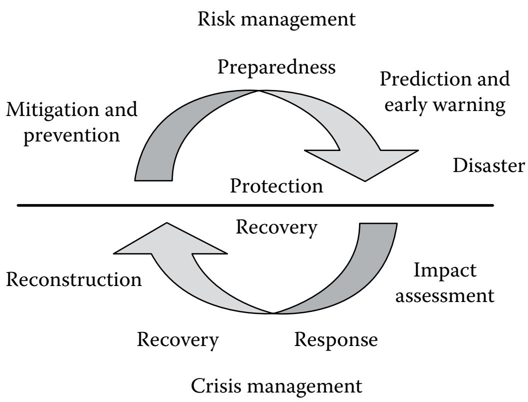

FIGURE 4.4 Disaster, risk, and crisis management cycle. (Adapted from Wilhite, D.A. et al., *J. Am. Water Resourc. Assoc.*, 36, 697, 2000.)

emphasis on crisis management such as food aid coming in as relief, communities have moved from one disaster to another with little, if any, reduction in risk [3].

4.7 Sensitivity to Impacts

Sensitivity refers to the degree a resource, population, etc., changes relative to incremental changes in the environment. As a result, sensitivity is a useful concept for describing how systems are more or less vulnerable to climate change. For example, a community water system with access to surface and groundwater resources is likely to be less vulnerable to water shortages than if it only had access to surface water, which may be reduced as a result of drier winters and reduced snowpack. There is significant variation in how animals, agricultural crops, rivers, etc., will be affected by drought. Also, vulnerability to extreme heat varies in a community because some individuals are more sensitive to heat-related stress and illness than others.

4.8 Exposure

Exposure to drought varies spatially and there is little, if anything, that can be done to alter the probability of its occurrence, yet vulnerability, on the other hand, is determined by social factors such as population size, demographic characteristics, policy, technology, social behavior, and coping strategies [23].

4.9 Capacity to Adapt to Impacts

The differential impacts of droughts on communities also mean that communities and individuals have different capacities to adapt. Adaptive capacity refers to the ability of natural, social, and economic systems to accommodate changes in climate, reduce or manage vulnerability, and limit adverse consequences.

It can reflect the intrinsic qualities of a system that make it more or less capable of adapting, such as the cooperative relationships between species in an ecosystem, the presence of effective leaders and organizers in a community, or the relative abundance of shaded parks in an urban environment. Adaptive capacity reflect the abilities of an organization responsible for managing ecosystems. The capacity to adapt is determined by a range of issues, including the ability to collect and analyze information, communicate, plan, and implement adaptation strategies that ultimately reduce vulnerability to climate change impacts.

Adaptive capacity is the ability of a system to adjust its characteristics or behavior in order to expand its coping range under existing climate variability or future climate conditions. Actions that lead to adaptation can enhance a system's coping capacity and increase its coping range, thereby reducing its vulnerability to climate hazards. The adaptive capacity inherent in a system represents the set of resources available for adaptation, as well as the ability or capacity of that system to use these resources effectively in pursuit of adaptation. Adaptive capacity helps to reduce vulnerability and increase resilience to climate change.

Organizations likely have access to a range of resources from which they can assess adaptive capacity, including the institutional knowledge of managers and staff, partner communities and stakeholders, and others. It is important that an assessment of adaptive capacity be informed by and reflective of exposure and sensitivity to climate impacts. In doing so, organizations can focus on adapting and how that adaptation may occur.

4.10 Coping and Coping Range

Coping is the manner in which people act within the confines of existing resources (e.g., land, livestock, draft animals, seed for crops, and labor) and the range of expectations to achieve various means [2,16]. It does not only involve the management of limited resources, but how it is done in unusual, abnormal, and adverse situations. The major objective of coping strategies is usually assumed to be survival in the face of adverse events; such an approach masks other important purposes as explained by Maslow's hierarchy of human needs [2,15]. Coping strategies may take various forms, some of which may even be prescribed and discouraged by members of a social group or gender. Coping range is the range in which the effects of climate conditions are beneficial or negative but tolerable. Beyond the coping range, the damage or losses are no longer tolerable and a society (or system) is said to be vulnerable.

4.11 Adaptation to Drought

In dealing with droughts or managing the impacts of drought, two approaches can be employed. One is to do nothing and another is to adapt. Adaptation as a strategy employed by all farmers is the most sustainable approach to drought mitigation through the establishment of strategic fodder reserves by the planting of fodder crops, conservation of forages, and storage for use at strategic times.

Adaptation refers to the ability of a system to adjust to a threat in order to reduce its vulnerability and enhance the resilience to observed and anticipated impacts of the threat. It is a process by which strategies to moderate, cope with, or take advantage of the consequences of climatic events are enhanced, developed, and implemented. The Intergovernmental Panel on Climate Change [12] defines adaptation as an "adjustment in natural or human systems to a new or changing environment. Adaptation refers to adjustment in natural or human systems in response to actual or expected stimuli or their effects, which moderates harm or exploits beneficial opportunities." In other words, adaptation can be understood as an ongoing process addressing many factors and stresses. Adaptation occurs in physical, ecological, and human systems. It involves the following: using scarce water resources more efficiently, adapting building codes to future climate conditions and extreme weather events, building flood defenses, developing drought-tolerant crops, choosing tree species and forestry practices less vulnerable to drought, and setting aside land corridors to help species migrate.

There are three adaptation approaches, namely, addressing vulnerability, building response capacity, and managing drought risk. Numerous drought control activities have been implemented especially for soil conservation, pasture improvement, livestock improvement, small-scale irrigation, cereal storage, agroforestry,

TABLE 4.8 Differences between Coping and Adaptation

Coping	Adaptation
Short-term and immediate	Practices and results are sustained
Oriented toward survival	Oriented toward longer-term livelihood security
Not continuous	A continuous process
Motivated by crisis; reactive	Involves planning
Often degrades the resource base	Uses resources efficiently and sustainably
Prompted by a lack of alternatives	Focused on finding alternatives
	Combines old and new strategies and knowledge

development of fuelwood resources, and also for nutrition improvement. Similarly, if adaptation measures (or the degree of preparedness) are strong, the lesser might be the impacts associated with any given degree of hazard. Depending on the timing, goal, and motive of its implementation, adaptation can be reactive, anticipatory, or autonomous. Table 4.8 shows the differences between coping and adaptation.

4.11.1 Types of Adaptation Measures

Adaptation means anticipating the adverse effects of a hazard and taking appropriate action to prevent or minimize the damage they can cause, or taking advantage of the opportunities that may arise. It has been shown that well-planned early adaptation action saves money and lives later. Adaptation measures depend on many factors. Accordingly, adaptation can include reactive or anticipatory actions, or can be planned or autonomous [12]. Alternatively, adaptation levels can be classified as local, national, regional, and global.

4.11.2 Reactive and Anticipatory

Reactive adaptation occurs after the initial impacts of drought become evident or have been felt. Anticipatory or proactive adaptation occurs before the impacts are obvious. For example, adaptation in a natural system is reactive by nature, while in a human system, it can be both reactive and anticipatory. Such anticipatory adaptation would progress from a top–down approach, through regulations, standards, and investment schemes. An anticipatory approach is particularly important for decisions that have long-term implications, such as the design and setting of long-lived infrastructure. By using climate models to gain an idea of future climate and climate variability, it is possible to reduce the impact of such events through anticipatory adaptation. Natural systems, such as plant and animal communities, always adapt reactively since they do not have the ability to plan ahead.

Both anticipatory and reactive adaptations by humans may further be categorized as either public or private. Public adaptation is normally facilitated by the government and aid agencies. Examples are the development of early warning systems, new building standards (anticipatory), and compensation payments to victims of floods or droughts (reactive). Private anticipatory adaptations may include, for example, building homes on stilts or purchasing insurance, whereas migration is a common reactive type of private adaptation.

4.11.3 Planned or Autonomous

Planned adaptation is the result of deliberate policy decision based on the awareness that conditions have changed or are expected to change and that some form of action is required to maintain a desired state. Planned adaptations include the following:

- Building up stocks for food and other saleable assets is one important coping strategy for people living in areas prone to drought to minimize the risks posed by extreme climatic variations [6,26].
- Credit.

- Insurance—for example, crop or livestock insurance.
- Diversification of crop production involves mixed cropping, intercropping, cultivation of nonstaple root crops, and the use of kitchen gardens. This provides a surplus in good years since it is normally planned on the basis of meeting subsistence needs in bad years [26].
- Income diversification, for example, blacksmithing, charcoal-making, honey collection, and crafts, has increasingly become important since it does not suffer directly from the impact of drought.

Spontaneous adaptation that is triggered by changes in natural systems or market or welfare changes, rather than a conscious response to an event, is also known as autonomous adaptation [12]. Autonomous adaptation refers to those actions that are taken as individual institutions, enterprises, and communities independently adjust to their perceptions of risk. Such autonomous actions may be short-term adjustments and are often considered as a reactive or bottom–up approach. Autonomous adaptations include the following:

- Adjustment of food habit, for example, food aid to meet food deficit requirements by donors, the government, and private organizations to avert hunger.
- Occupational diversification—employing other sources of household income other than the dominant one, for example, casual labor, petty trading, cross-border trading, and artisanal work.
- Distress sale—for example, selling off productive disposable assets (such as livestock and building material).
- Social support networks—for example, strategic early marriages of daughters or sons into comparatively wealthy family.
- Antisocial behaviors—for example, illegal border jumping [15].
- Many male heads of households migrate, following a disaster, due to frustration at not being able to fulfill one's role as breadwinner and the intention to seek work and send remittances to the family. But it results in an increase in the number of female heads of households [2,6].
- Taking children out of school in response to adverse income shocks. The result is lower accumulation of human capital [6,14].

4.11.4 Sectoral Adaptation

Sectoral adaptation measures aim at actions for individual sectors that could be affected by drought. For example, in agriculture, reduced rainfall and higher evaporation rates would call for new irrigation practices. Such a change would require a national policy framework, which integrates traditional coping mechanisms along with new practices and emphasizes on the importance of including climate change as a long-term consideration while formulating policies.

4.11.5 Multisectoral Adaptation

This approach aims at actions that originate from various sectors. It is like looking at a particular problem through different lenses. It cuts across various sectors, for example, integrated management of water, river basins, or coastal zones. Linking adaptation to climate change could serve as a multisectoral approach.

4.11.6 Cross-Sectoral Adaptation

This is an integrated or holistic approach taking into consideration, for example, science, research and development, and technological innovations such as the development of drought-resistant crop varieties or new technologies to combat saltwater intrusion.

4.12 Case Study: Coping with Drought in Chiredzi Rural District, Zimbabwe

4.12.1 Background

Chiredzi rural district lies to the south-eastern lowveld of Zimbabwe. In 2013, its population stood at 276 842 [27]. A community participatory climate risk analysis for Chiredzi rural district revealed that drought is the most important climatic hazard in the district. Five types of drought are normally experienced in the district; these are early season (characterized by delayed or slow onset of the rains), mid-season (rains break for weeks on end about January/February), terminal (rains just terminate from about January/February), seasonal (rains are light and patchy throughout the season), and extreme drought (in this case, rains fail for two or more consecutive seasons). The extreme drought type usually calls for state intervention to save livestock and human lives. The district experienced droughts in 1947, 1948, 1965, 1966, 1968, 1969, 1982, 1983, 1984, 1987, 1991, 1992, 1995, 1996, 2001, 2002, 2006, 2007, and 2008, some of which had severe impacts on rural livelihoods [8].

4.12.2 Drought Impacts in Chiredzi Rural District

Impacts of drought in Chiredzi rural district are as follows [8]:

- *Livelihoods*: Crop failure and lack of fodder and water for cattle and irrigation
- *Food security*: Reduced availability of nutritious food
- *Health*: Insufficient water for hygiene purposes, increase in diarrheal diseases and stress associated with loss of livelihoods
- *Economic*: Increased prices of food and fodder, loss of income from agriculture and employment
- *Social*: Migration and associated impacts on families, increased inequity among social groups, increase in crime, increase in school dropouts, increased burden on women and children, increased burden on government and relief agencies
- *Environmental*: Increased deforestation, loss of biodiversity, and saline water intrusion

4.12.3 Vulnerability of Crop and Livestock Production Systems to Drought in Chiredzi Rural District

Adaptive capacity across Chiredzi rural district for both crop and livestock production livelihood systems has been shown to decrease from north to south. Vulnerability "hot spots" are mainly concentrated in the southern sections of the district. Rain-fed cropping systems and livestock production systems based on cattle have been identified as the most vulnerable livelihood systems.

The exposure of Chiredzi rural district and the sensitivity of crop and livestock production systems to drought are a result of socioeconomic and technological factors (such as access to markets, communication infrastructure, irrigation facilities, seed technology, institutions, etc.).

4.12.3.1 Drivers of Vulnerability

The vulnerability of Chiredzi rural district to drought can be ascribed to inherent dryness, a high frequency of drought, monocropping (overdependence on maize), poor farming practices, a high incidence of poverty, limited alternative livelihood options outside agriculture, low access to technology (e.g., irrigation and seed), markets, institutions, and infrastructure (e.g., poor roads, bridges, modern energy, dams, and water conveyance), population pressure, skewed ownership and access to drylands livelihood assets such as livestock and wildlife, lack of drought preparedness plans, and limited use of drought early warning systems [8].

Lack of access to markets, institutions, poverty, communication infrastructure (all-weather roads, bridges), and high frequency of drought were some of the main drivers of vulnerability identified.

4.12.4 Adaptation Options

4.12.4.1 Autonomous Adaptation Strategies

Prevailing autonomous adaptation strategies are in agriculture, livestock production, water resources, food and economic security. Traditional agriculture had survival strategies built into it. In the past, most crop lands would hold two or more crops intercropped and a range of other crops to reduce the chances of total harvest loss should the rains fail. Currently, production of drought-tolerant crop varieties (particularly small grains), livestock farming, and remittances are the most important household drought risk management strategies cited by farmers from the project area [8].

4.12.4.2 Planned Adaptation Actions

The central government and local authorities are responsible for developing national- and regional-level development strategies and programs. Development strategies have prioritized the following adaptation strategies in Chiredzi rural district, mainly in response to the problem of recurrent droughts [8]:

- *Agriculture*: Extend irrigation facilities, provide drought-tolerant open-pollinated maize and sorghum seeds, promote small-grains and matching livestock numbers to the carrying capacity of the area, practice conservation agriculture, and establish farmer field schools.
- *Water*: Building dams and drilling boreholes, enforcing water rights, and improving water use efficiency.
- *Food security/safety-strategic grain reserves*: Develop village seed banks with seeds of traditional and improved drought-resistant crops/varieties.
- *Livestock production*: Promote the rearing of goats and donkeys in areas where feed and water are scarce; promote the rearing of drought-resistant local cattle breeds, grasses, and perennial fodder trees in community forest, fallow lands, and permanent pastures; promote indigenous drought fodder and other fodder trees discovered by local farmers in recent droughts; construct rainwater-harvesting structures (e.g., miniponds, tanks); and improve veterinary services.

Thus, drought is the main climatic hazard affecting Chiredzi rural district. The district is prone to early, mid-, terminal, seasonal, and extreme droughts that can last for up to 4 years in succession. Terminal, seasonal and extreme drought types are having the worst impacts on the livelihoods of the people of the district [8].

4.13 Summary and Conclusions

Drought is the most important and most complex natural disaster in economic, social, and environmental terms. It is the least understood of all natural hazards and the one causing serious adverse effects on societies and national economies, as well as on critical human and material resources. By definition, drought is a consequence of a natural reduction in the amount of precipitation received over an extended period of time, usually a season or more, and is also related to the timing and effectiveness of rains, such as delays in the beginning of the rainy season, the occurrence of rains in relation to crop growth stages, rainfall intensity, and the number of rainfall events. Drought is a temporary aberration, in contrast to aridity, which is a permanent feature of the climate of low-rainfall areas. Drought is a normal, recurring feature of the climate and occurs virtually in all climatic regimes, in high- as well as low-rainfall areas.

Drought severity is dependent not only on the duration, intensity, and geographical extent of a specific episode but also on the demands made by human activities and vegetation on an area's water supplies. The characteristics of drought, along with its far-reaching impacts, make its effects on society and the environment difficult, though not impossible, to identify and quantify.

Drought can occur at such times when variables such as rainfall depth, runoff, soil moisture, etc., show a deficiency, when variables such as temperature show an increase, or when groundwater level shows a decrease in comparison with the average level. Drought can be evaluated with respect to agricultural, meteorological, or hydrological variability. In this context, communities at risk find themselves even more vulnerable because of several aggravating factors, including poverty, environmental degradation, inadequate exchange of data and information, and inadequate coordination at the continental level. Therefore, local communities should be considered as primary actors in the design, adoption, and implementation of drought reduction policies and measures through investing in soil and water management, such as the improved development and management of fragile catchment areas and river basins, including small-scale irrigation; reviewing the appropriateness of current crop production patterns and possibilities in support of more intensified crop diversification policies; redirecting research toward more appropriate farming systems; improving rangeland and livestock management; and reviewing institutional arrangements and physical infrastructure.

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5

Drought Management Strategies in Water-Stressed/ Water-Scarce Regions

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Abstract Water scarcity and drought affect all social and economic sectors and threaten the sustainability of natural resources. Addressing water scarcity requires an intersectoral and multidisciplinary approach to managing water resources in order to maximize economic and social welfare in an equitable manner without compromising sustainability of vital ecosystems. Integration across sectors is needed. This integration needs to take into account development, supply, use, and demand and to place the emphasis on people, their livelihood, and ecosystems that sustain them. On the demand side, enhancing water productivity (the volume of production per unit of water) in all sectors is paramount to the success of programs intended to alleviate water scarcity. Furthermore, protecting and restoring the ecosystems that naturally capture, filter, store, and release water, such as rivers, wetlands, forests, and soils, are crucial to increasing the availability of water of good quality. It is in this context that this chapter provides further insight to the global challenges faced in the context of water scarcity and drought. Some of the strategic solutions developed in different parts of the world are discussed to understand implications on the sustainability and efficient use of resources.

5.1 Introduction

Water scarcity is defined as the point at which the aggregate impact of all users impinges on the supply or quality of water under prevailing institutional arrangements to the extent that the demand by all sectors, including the environment, cannot be fully satisfied. Water scarcity is a relative concept and can occur at any level of supply or demand. Scarcity may be a social construct (a product of affluence, expectations, and customary behavior) or the consequence of altered supply patterns—stemming from climate change, for example. A society facing water scarcity usually has options. However, scarcity often has its roots in water shortage, and it is in the arid and semiarid regions affected by droughts and wide climate variability, combined with high population growth and economic development, that the problems of water scarcity are most acute [37].

Wilhite [124,125] highlighted that drought is a normal, recurring feature of climate; it occurs in virtually all climatic regimes. It occurs in high as well as low rainfall areas. It is a temporary aberration, in contrast to aridity, which is a permanent feature of the climate and is restricted to low rainfall areas. Drought is the consequence of a natural reduction in the amount of precipitation received over an extended period of time, usually a season or more in length, although other climatic factors (such as high temperatures, high winds, and low relative humidity) are often associated with it in many regions of the world and can significantly aggravate the severity of the event. Drought is also related to the timing (i.e., principal season of occurrence, delays in the start of the rainy season, occurrence of rains in relation to principal crop growth stages) and the effectiveness of the rains (i.e., rainfall intensity, number of rainfall events). Thus, each drought year is unique in its climatic characteristics and impacts [127].

Over the past decades, changing hydroclimatic and socioeconomic conditions increased regional and global water scarcity problems [22,65,114,116,117]. Future climate change, projected population growth, and continuing increase in water demand are expected to aggravate these water scarcity conditions worldwide [4,24,26,48,63,65,68,87,93,94,96,97,111,112,119,115].

Some examples of the current sensitivities of the global freshwater system are explained in the following and highlighted in Figure 5.1 [55]. The sensitivities are quantified through the use of water stress indicator expressed as the ratio of withdrawal to availability:

- Droughts, affecting rained agricultural production as well as water supply for domestic, industrial, and agricultural purposes, are experienced in some of the semiarid and subhumid regions of the globe, for example, Australia, western United States [82], and southern Canada.
- In snow-dominated basins, higher temperatures lead to reduced streamflow and thus decreased water supply in summer [9], for example, in South American river basins along the Andes, where glaciers are shrinking [20].
- Currently, human beings and natural ecosystems in many river basins suffer from a lack of water. In global-scale assessments, basins with water stress are defined either as having a per capita water availability below 1000 m^3/year (based on long-term average runoff) or as having a ratio of withdrawals to long-term average annual runoff above 0.4. These basins are located in Africa, the Mediterranean region, the Near East, South Asia, Northern China, Australia, the United States, Mexico, northeastern Brazil, and the western coast of South America (Figure 5.1). Estimates of the population living in such severely stressed basins range from 1.4 to 2.1 billion [3,7,85,114]. In water-scarce areas, people and ecosystems are particularly vulnerable to decreasing and more variable precipitation due to climate change. For example, as per the applications of Yang et al. [135], in the Huanghe River basin in China, the combination of increasing irrigation water consumption facilitated by reservoirs and decreasing precipitation associated with global El Niño–Southern Oscillation (ENSO) events over the past half century has resulted in water scarcity [120].
- With more than one-sixth of the Earth's population relying on meltwater from glaciers and seasonal snow packs for their water supply, the consequences of projected changes for future water availability, predicted with high confidence and already diagnosed in some regions, will be adverse

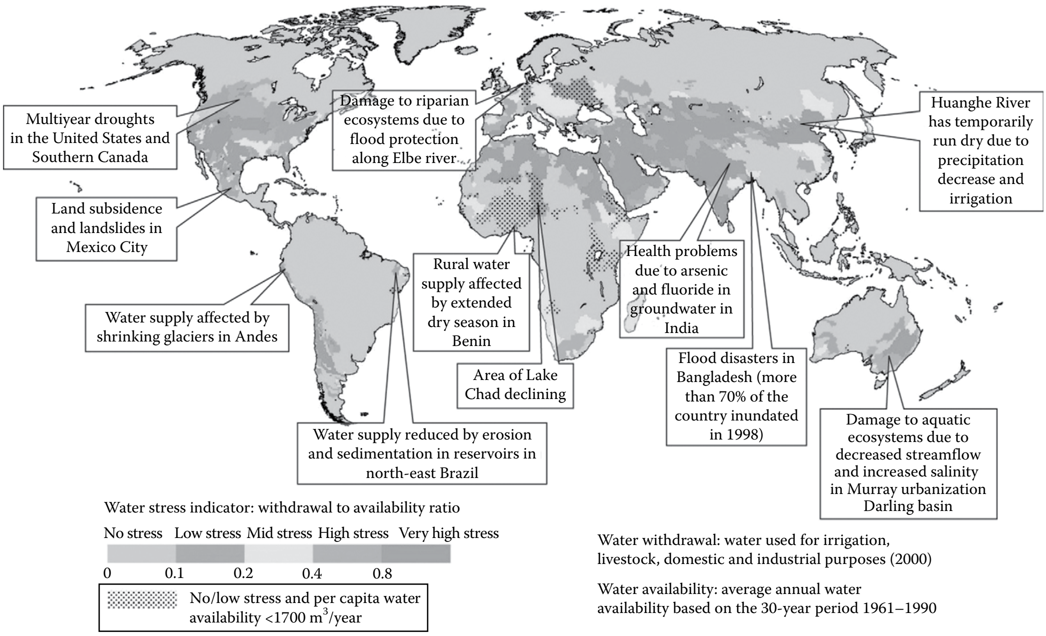

FIGURE 5.1 Examples of current vulnerabilities of freshwater resources and their management. (From IPCC, Climate change 2007: Impacts, adaptation and vulnerability, *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., and Hanson, C.E. (eds.), Cambridge University Press, Cambridge, U.K., 2007, 976pp.)

and severe. Barnett et al. [9] projected drought problems for regions that depend heavily on glacial meltwater for their main dry season water supply. In the Andes, glacial meltwater supports river flow and water supply for tens of millions of people during the long dry season. Many small glaciers, for example, in Bolivia, Ecuador, and Peru [20], will disappear within the next few decades, adversely affecting people and ecosystems.

In many regions of the globe, climate change impacts on freshwater resources will affect sustainable development and put it at risk. Even with optimal water management, it is very likely that negative impacts on sustainable development cannot be avoided. Figure 5.2 shows some key cases around the world where freshwater-related impacts are a threat to the sustainable development of the affected regions. Background map reflects ensemble mean change of annual runoff, in percent, between the present (1981–2000) and 2081–2100 for the Special Report on Emissions Scenarios (SRES) A1B emission scenario. A total of six key cases presented reflect the works of Bobba et al. (Case 1) [13], Barnett et al. (Case 2) [10], Doll and Florke (Case 3) [25], Mirza et al. (Case 4) [77], Lehner et al. (Case 5) [69], and Kistemann et al. (Case 6) [64].

It is evident that sustainable use of water resources is at significant risk. This requires strategic rethinking by integrating processes and activities and considering energy, equity, health, and water governance components, which is the fundamental framework of water–energy–food nexus. In this context, the nexus approach has emerged as a useful concept to describe and address the complex and interrelated nature of our global resource systems, on which we depend to achieve different social, economic, and environmental goals [40,46,47].

In practical terms, it presents a conceptual approach to better understand and systematically analyze the interactions between the natural environment and human activities and to work toward a more coordinated management and use of natural resources across sectors and scales. This can help us to identify and manage trade-offs and to build synergies through our responses, allowing for more integrated and

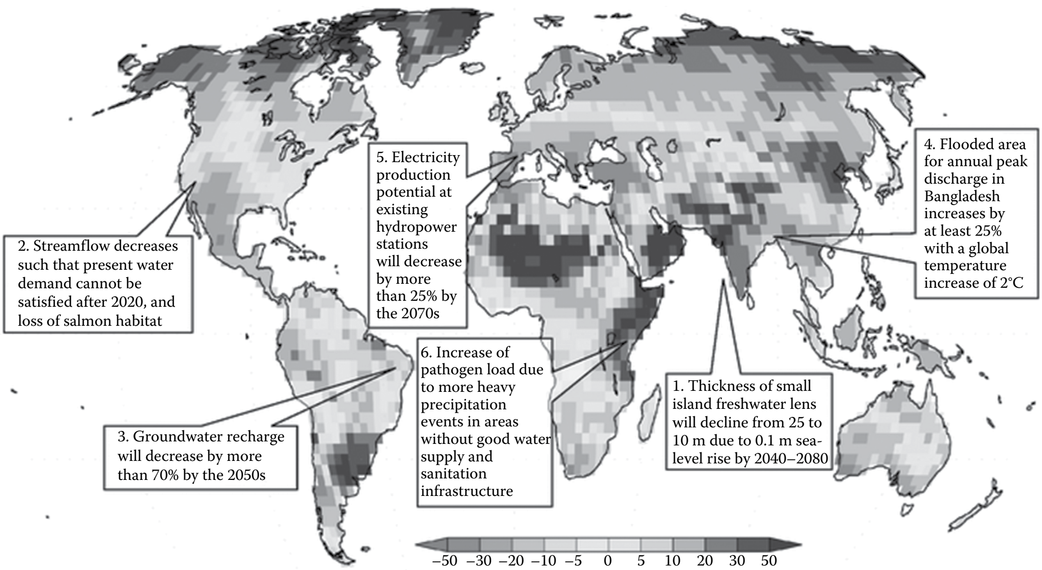

FIGURE 5.2 Map of future climate change impacts on freshwater, which are a threat to the sustainable development of affected regions. (From IPCC, Climate change 2007: Impacts, adaptation and vulnerability, *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., and Hanson, C.E. (eds.), Cambridge University Press, Cambridge, U.K., 2007, 976pp.)

cost-effective planning, decision-making, implementation, monitoring, and evaluation. Nexus interactions are complex and dynamic, and sectoral issues cannot be looked at in isolation from one another. Importantly, they exist within a wider context of transformational processes—or drivers of change—that need to be taken into account. It is important to note that there are different conceptualizations of the nexus that vary in their scope, objectives, and understanding of drivers. Several concepts, frameworks, and methodologies have looked at the interlinkages between not only water, energy, and food [8,12,78,104] but also land and soil [30] and ecosystems [54].

5.2 Regions Facing Water Stress and Scarcity

5.2.1 Basic Definitions

It is important to understand distinct features of water scarcity, water stress, and water risk as defined in the following sections (Figure 5.3).

5.2.1.1 Water Scarcity

"Water scarcity" refers to the volumetric abundance, or lack thereof, of water supply. This is typically calculated as a ratio of human water consumption to available water supply in a given area. Water scarcity is a physical, objective reality that can be measured consistently across regions and over time [84].

5.2.1.2 Water Stress

"Water stress" refers to the ability, or lack thereof, to meet human and ecological demand for water. Compared to scarcity, "water stress" is a more inclusive and broader concept. It considers several physical aspects related to water resources, including water scarcity, but also water quality, environmental flows, and the accessibility of water.

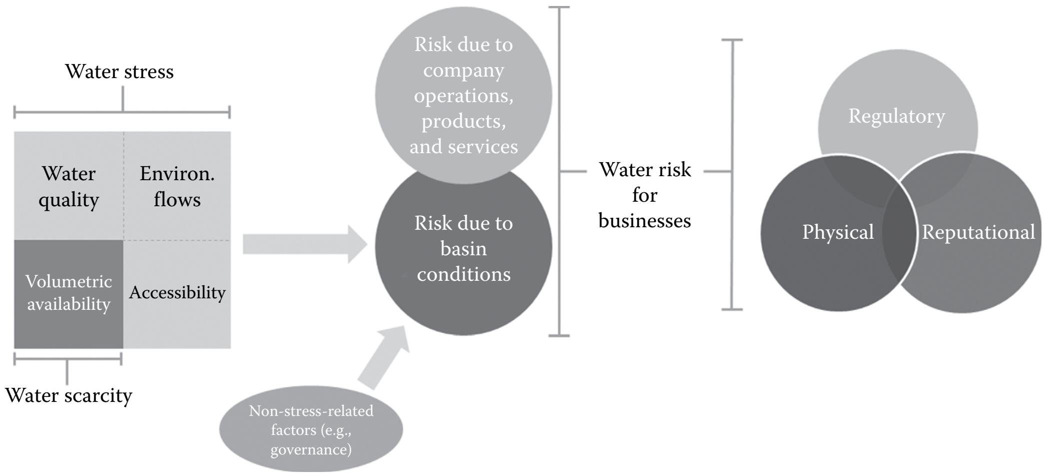

FIGURE 5.3 Relation between water stress and water scarcity. (From Schulte, P., *Defining Water Scarcity, Water Stress, and Water Risk: It's Not Just Semantics*, Pacific Institute Insights, Oakland, CA, 2014.)

5.2.1.3 Water Risk

"Water risk" refers to the probability of an entity experiencing a deleterious water-related event. Water risk is felt differently by every sector of the society and the organizations within them and thus is defined and interpreted differently (even when they experience the same degree of water scarcity or water stress). That notwithstanding, many water-related conditions, such as water scarcity, pollution, poor governance, inadequate infrastructure, and climate change, create risk for many different sectors and organizations simultaneously.

In this context, the functional relationship between water scarcity, water stress, and water risk can be described as follows. "Water scarcity" is one aspect of many that contributes to and informs "water stress." An area could conceivably be highly water stressed, but not water scarce, if, for example, it had egregious water pollution, but plentiful supplies of contaminated water. "Scarcity" and "stress" both directly inform an understanding of "risks due to basin conditions." It is not possible to gain robust insight into water risk unless a firm understanding of the various components of water stress (i.e., water scarcity, accessibility, environmental flows, and water quality) as well as additional factors, such as water governance, is in place.

5.2.2 Background

The regions most vulnerable to water scarcity and drought are located in sub-Saharan Africa and Central Asia. Over the last four decades, the African continent has suffered seven major drought episodes. In two regions—the Sahel and the Horn of Africa—droughts in 1972–1974 and 1981–1984 caused massive social disruption and human suffering. And the problem is likely to become worse, according to recent studies, if trends in climate change play out as expected.

Recent years include the most dreadful droughts in the Horn and severe droughts in 2009 and 2011 in Kenya. Available crop data for 2009 indicate that Kenya's agriculture was the most severely affected, with wheat yields dropping by 45% compared to 2010s good crop season. Australia suffered multiyear droughts between 2002 and 2010. Based on FAO statistics, total Australia wheat yield in 2006 dropped by 46% (below 1960–2010 yield trend level).

The 2010 drought in Russia was very long and intensive, spread over a sizeable area, and caused serious damage to the environment, economy, and human health. The 2010 drought was the worst in the last 38 years in Russia.

The 2011 U.S. drought covered southern states; Texas, Oklahoma, and New Mexico were most adversely affected. Drought also affected parts of Arizona, Kansas, Arkansas, Georgia, Florida, Mississippi, Alabama, and South and North Carolina. The extreme U.S. great grain belt drought of 2012 was forecast to persist into spring of 2013. Drought in large parts of the United States also pushed up world food prices, exerting pressure on the cost of living and affecting food security [39]. With California facing one of the most severe droughts on record, a Drought State of Emergency was declared in January 2015 and state officials were directed to take all necessary actions to prepare for water shortages. The state has continued to lead the way to make sure California is able to cope with an unprecedented drought.

In 2012, a devastating drought in southwestern China's Yunnan Province entered its third year. The drought has already affected more than 6.3 million people; 2.4 million experience difficulty in seeking access to drinking water. Southwestern China's agricultural industries have also been critically affected, having lost approximately 2 billion yuan. Although farmers have switched to more resistant crops, this has still not alleviated many of the problems created by the drought. Families in some regions have been reduced to transporting water from more than 10 km away. China has long been affected by desertification in the northern and western regions, but the drought in Yunnan marks a new high in China's difficulties with the climate and environment.

5.2.3 Dimensions of Water Scarcity

The causes of scarcity, as indicated in the chosen definition, may be of a varying nature, requiring specific responses. The Comprehensive Assessment of Water Management in Agriculture states that water scarcity is a critical constraint to agriculture in many parts of the world. Based on prior work by Seckler et al. [95], it distinguishes two main types of water scarcity, namely, physical scarcity and economic scarcity.

1. *Physical water scarcity* is said to occur when there is not enough water to meet all demands, including environmental flows. Symptoms of physical water scarcity are severe environmental degradation, declining groundwater, and water allocations that favor some groups over others.
2. *Economic water scarcity* is described as a situation caused by a lack of investment in water, or a lack of human capacity to satisfy the demand for water. Symptoms of economic water scarcity include scant infrastructure development, either small or large scale, leading to people having trouble getting enough water for agriculture. Most countries located in sub-Saharan Africa are characterized by economic scarcity, so further water development could do much to reduce poverty.

In a recent report on water scarcity in the Middle East, the World Bank suggests considering three types of water scarcity: scarcity of the physical resource, organizational scarcity, and scarcity of accountability. Organizational scarcity refers to "getting water to the right place at the right time." Accountability refers to government's accountability to their constituencies and service providers' accountability to their users [130]. The emphasis on issues that can be broadly considered as institutional is representative of the current trends toward increasing attention being given to management, as supply options reach their limits.

Building on these and other approaches and acknowledging that scarcity is the result of multiple causes, and therefore requires different responses, three main dimensions of water scarcity can be summarized as follows [38]:

1. Scarcity in availability of water of acceptable quality with respect to aggregated demand, in the simple case of physical water shortage.
2. Scarcity due to the lack of adequate infrastructure, irrespective of the level of water resources, because of financial, technical, or other constraints.
3. Scarcity in access to water services, because of the failure of institutions (including legal rights) in place to ensure reliable, secure, and equitable supply of water to users. This dimension brings together the organizational and accountability dimensions proposed by the World Bank [130].

In the last two cases, countries may have a relatively high level of water resources endowment compared with demand, but may be unable to capture and distribute them because of lack of infrastructure, or institutional factors limiting access to water.

5.2.4 Indicators of Water Scarcity

The best-known indicator of national water scarcity is per capita renewable water, where threshold values of 500, 1000, and 1700 m^3/person/year are used to distinguish between different levels of water stress as presented by Falkenmark and Widstrand [35] and documented in UN-Water [110].

On this criterion, countries or regions are considered to be facing *absolute water scarcity* if renewable water resources are less than 500 m^3/capita, *chronic water shortage* if renewable water resources are between 500 and 1000 m^3/capita, and *regular water stress* if renewable water resources are between 1000 and 1700 m^3/capita (Table 5.1). Falkenmark [34] implemented this crude approach to measuring water scarcity that was primarily based on estimates of the number of people who can reasonably live with a certain unit of water resources. This indicator is widely used because it can be easily calculated for every country in the world and for every year, based on water resources data presented in FAO AQUASTAT [42] and available population data by the World Bank [131]. Furthermore, population projections, currently extending to the year 2100, also allow for projection of water scarcity levels in the forthcoming decades.

Global distribution of water stress and scarcity as defined by Falkenmark [34] is depicted in Figure 5.4. It is evident that conditions are the worst for the Middle East and North Africa, sub-Saharan Africa, and Central Asia.

The dependency in water resources to upstream sources makes livelihoods more challenging. In this context, dependency ratio (Figure 5.5) is a good indicator of where tension and conflict over water sharing and use can occur. Some of the well-known areas include central Asia, the Middle East (especially Syria and Iraq), India, and Pakistan and, surprisingly, lowland countries such as the Netherlands.

Although Falkenmark's measure has its merits, it oversimplifies the water situation of specific countries, ignoring local factors determining access to water, as well as the feasibility of solutions in different locations. Molle and Mollinga [82] pointed out that it cannot take into account prevailing climatic conditions: inter- and intra-annual variability of water resources; governance; issues of water access, water rights, and social exclusion; competition between sectors; potential for recycling of water or development of unconventional water resources; and environmental water requirements, which will vary from region to region. Averages at the country level are also not very meaningful, in particular for large countries with strong regional variations.

In an attempt to better capture the relation between supply and demand, the Millennium Development Goals water indicator, as represented through FAO AQUASTAT [42], purports to measure the level of human pressure on water resources based on the ratio between total water withdrawal by agriculture, cities, and industries over total renewable water resources. While such an indicator reflects the balance between supply and demand, it entails computational and conceptual problems, related in part to the reliability of measurement of water withdrawal, issues of double accounting (reuse of drainage water or return flow), the absence of systematic time series of the data needed for long-term monitoring, and difficulties in interpreting trends.

Another water stress index, based on "the percentage of water demand that cannot be satisfied without taking measures" [110], was developed in an attempt to focus attention on remedial action and recognize

TABLE 5.1 Conventional Definitions of Levels of Water Stress

Annual Renewable Freshwater (m^3/Pers. Year)	Level of Water Stress
<500	Absolute water scarcity
500–1000	Chronic water shortage
1000–1700	Regular water stress
>1700	Occasional or local water stress

Source: Falkenmark, M. and Widstrand, C., *Population and Water Resources: A Delicate Balance*, Population Bulletin, Population Reference Bureau, Washington, DC, 1992.

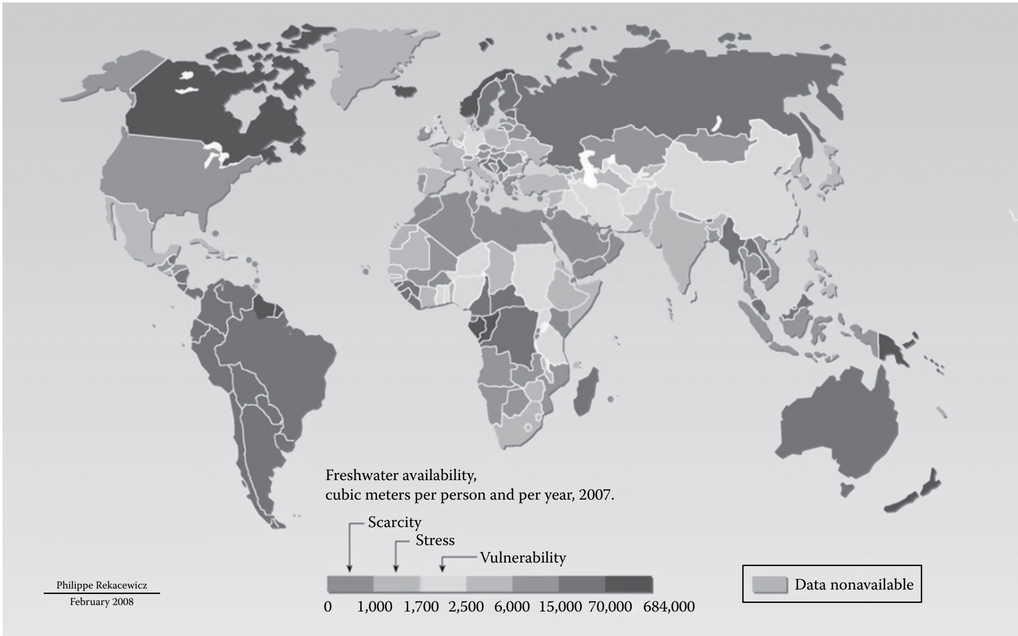

FIGURE 5.4 Global water stress and scarcity. (From FAO, Nations unies, World Resources Institute; Tate, E.L. and Gustard, A., Drought definition: A hydrological perspective, in Vogt, J.J. and Somma, F. (eds.), *Drought and Drought Mitigation in Europe*, Kluwer, Dordrecht, the Netherlands, 2000, pp. 23–48.)

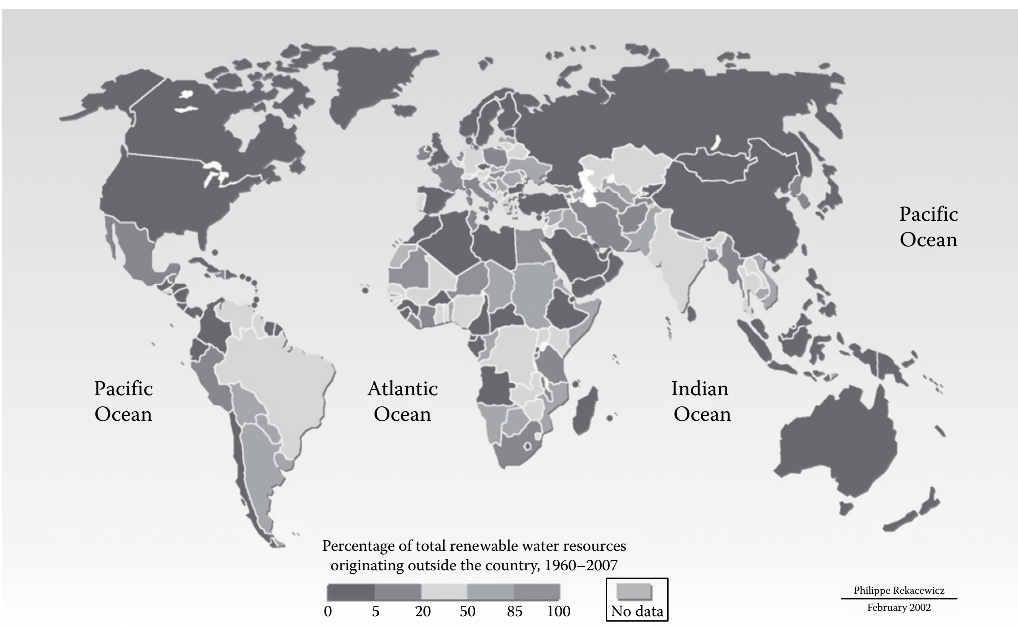

FIGURE 5.5 Dependency ratio in renewable water. (From FAO, Aquastat, 2007; Tate, E.L. and Gustard, A., Drought definition: A hydrological perspective, in Vogt, J.J. and Somma, F. (eds.), *Drought and Drought Mitigation in Europe*, Kluwer, Dordrecht, the Netherlands, 2000, pp. 23–48.)

the dynamic nature of water scarcity. While none of these attempts to quantify water scarcity and related water stress are perfect, they reflect the relative nature of water scarcity and offer firsthand assessment of the dimension of the problem at the level of a country or region.

In water-scarce regions, as is the case for the Middle East and North Africa, ratio between annual freshwater withdrawals and renewable internal freshwater resources is quite high (121.9%), which indicate a severely stressed condition (Table 5.2), and the region is considered as water scarce. The variation across the globe (Figure 5.6) reveals that South America, South Africa, Australia, and South Asia can be considered in high stress category. A similar outcome is evident using most populous river basins (Figure 5.7).

A good example of economic scarcity is experienced in sub-Saharan Africa. Even though average per capita renewable freshwater water of 4120 m^3/capita is higher than of the Euro zone (2991 m^3/capita), lack of investment and inability to utilize water resources place significant stress, which results in high level of water scarcity.

The relevance of the problems of water scarcity is evidenced further when considering that estimates for the average annual growth of the population are the world's highest in the same regions: 27.0% for 2000–2014 and 17.5% for 2014–2025 for Middle East and North Africa and 44.9% and 31.9% for the same periods in sub-Saharan Africa (Table 5.3).

A strategic approach, as introduced by Gassert et al. [45], makes use of a framework (Table 5.4) that includes 12 global indicators grouped into three categories of risk and one overall water risk index. The composite overall water risk index (Figure 5.8) highlights regions of high risk. This index is best suited for comparative analyses across large geographies to identify regions or assets deserving closer attention and is not appropriate for catchment or site-specific analyses. Indeed, global-scale indices such as this face significant limitations in their ability to accurately and objectively capture most aspects of the underlying phenomena at specific places.

Forecasts show that water scarcity or water stress may affect a very large number of countries. Overall results show rapid increases in water stress across many regions including the Mediterranean, the Middle East, the North American West, eastern Australia, western Asia, northern China, and Chile (Figure 5.9). Regions that increase in stress but remain at low stress levels (<0.1) and regions that decrease in stress but remain at extremely high stress levels (>0.8) are shown as "near normal." Changes in water demand, driven by socioeconomic growth, are more dominant than changes in water supply, driven by climate as documented by Luck et al. [71]. These results raise three points:

1. Understanding growth in demand is at least as important as understanding changes in supply.
2. Water managers may have the opportunity to avoid the majority of water stress increases through improved water demand management.
3. In many areas, decision-makers must be prepared for a wide range of possible outcomes.

The scenarios are based on a combination of projected water supply based on change in climate factors and water demand based on change in socioeconomic drivers.

5.2.4.1 Representative Concentration Pathways (RCPs)

Representative concentration pathways are scenarios of the increase in radiative forcing through 2100. These drive the climate factors in the general circulation models:

- RCP8.5 is a "business-as-usual" scenario of relatively unconstrained emissions. Temperatures will increase 2.6°C–4.8°C by 2100 relative to 1986–2005 levels.
- RCP4.5 represents a "cautiously optimistic" scenario. Temperatures will rise 1.1°C–2.6°C by 2100.

5.2.4.2 Shared Socioeconomic Pathways (SSPs)

Shared socioeconomic pathways are scenarios of socioeconomic drivers:

- SSP2 is a "business-as-usual" scenario.
- SSP3 is a "pessimistic" scenario with higher population growth, lower GDP growth, and a lower rate of urbanization.

TABLE 5.2 World Availability of Water Resources

	Internal Renewable Freshwater Resources		Annual Freshwater Withdrawals					Water Productivity	Access to an Improved Water Source	
	Flows Billion cu. m 2013	Per capita cu. m 2013	Billion cu. m 2013	% of Internal 2013	% for Agriculture 2013	% for Industry 2013	% of Domestic 2013	GDP/Water Use 2005 $ per cu. m 2013	% of Rural Population 2012	% of Urban Population 2012
Low and middle income	27,467.0	4,791	2812.2	10.3	81	10	10	5	80	95
High income	15,454.0	11,404	1094.5	7.1	44	39	16	38	98	100
Sub-Saharan Africa	3,857.8	4,120	116.2	3	81	5	14	9	53	85
East Asia and Pacific	8,773.2	4,376	949.3	10.9	73	17	10	7	85	97
South Asia	1,982.2	1,186	1023.4	51.6	91	2	7	2	89	95
Europe and Central Asia	725.4	2,790	226.0	31.1	69	20	11	5	89	99
Middle East and North Africa	226.5	656	276.1	121.9	86	6	8	3	83	95
Latin America and Caribbean	11,902.0	23,079	221.2	1.9	70	12	19	13	82	97
Euro area	1,008.8	2,991	189.2	18.7	31	52	17	58	100	100
World	42,921.0	6,055	3906.7	9.1	71	18	12	14	82	96

Source: World Bank, *World Development Indicators*, World Bank, Washington, DC, 2015.

Renewable internal freshwater resources, total (billion cubic meters): Renewable internal freshwater resources flows refer to internal renewable resources (internal river flows and groundwater from rainfall) in the country and region.

Annual freshwater withdrawals, total (*billion cubic meters*): Annual freshwater withdrawals refer to total water withdrawals, not counting evaporation losses from storage basins. Withdrawals also include water from desalination plants in countries where they are a significant source. Withdrawals can exceed 100% of total renewable resources where extraction from nonrenewable aquifers or desalination plants is considerable or where there is significant water reuse.

Withdrawals for agriculture and industry are total withdrawals for irrigation and livestock production and for direct industrial use (including withdrawals for cooling thermoelectric plants). Withdrawals for domestic uses include drinking water, municipal use or supply, and use for public services, commercial establishments, and homes.

Improved water source, rural (*% of rural population with access*): Access to an improved water source refers to the percentage of the population using an improved drinking water source. The improved drinking water source includes piped water on premises (piped household water connection located inside the user's dwelling, plot, or yard) and other improved drinking water sources (public taps or standpipes, tube wells or boreholes, protected dug wells, protected springs, and rainwater collection).

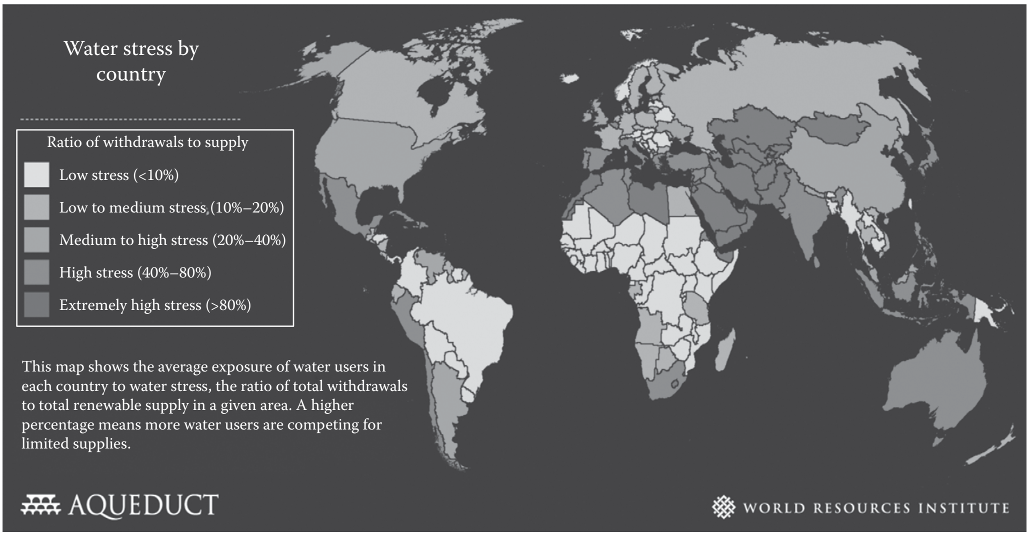

FIGURE 5.6 Global water stress by country. (From WRI Aqueduct; Gassert et al. (2013); Luck, M. et al., Aqueduct water stress projections: Decadal projections of water supply and demand using CMIP5 GCMs, Technical Note, World Resources Institute, Washington, DC, Available online at: wri.org/publication/aqueduct-water-stress-projections, 2015.)

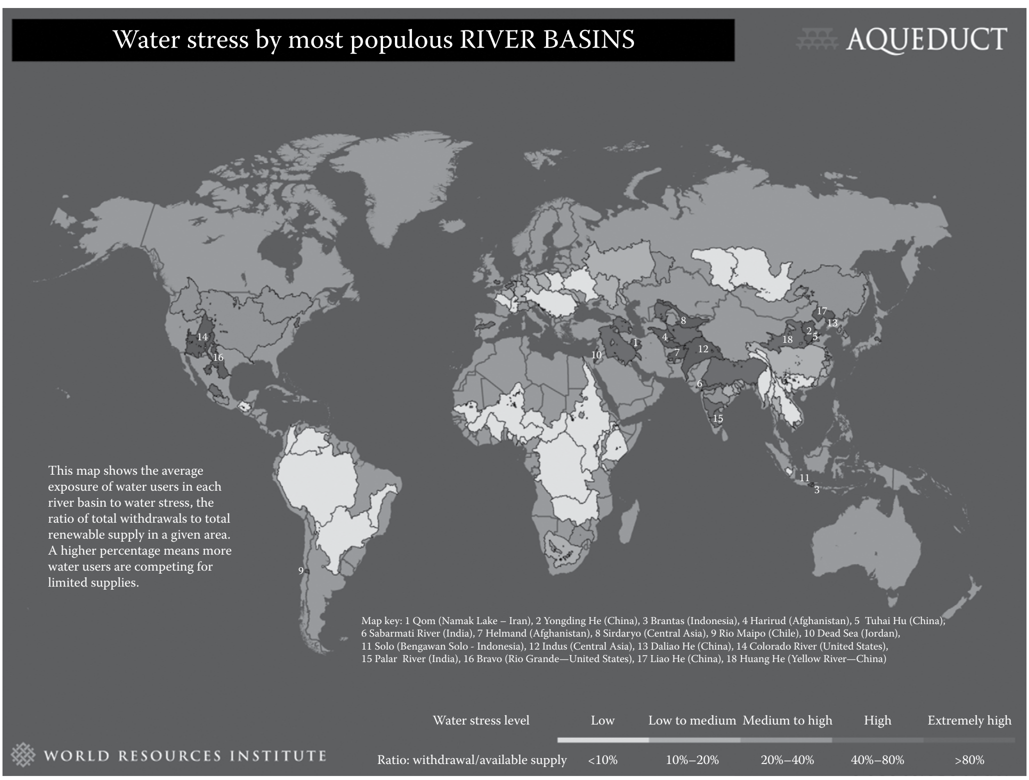

FIGURE 5.7 Global water stress by most populous river basins. (From Luck, M. et al., Aqueduct water stress projections: Decadal projections of water supply and demand using CMIP5 GCMs, Technical Note, World Resources Institute, Washington, DC, Available online at: wri.org/publication/aqueduct-water-stress-projections, 2015.)

TABLE 5.3 Population and Average Annual Growth

	Population (Millions)			Average Annual Population Growth (%)	
	2000	2014	2025	2000–2014	2014–2025
World	6102.0	7207.7	8036.6	18.1	11.5
Low income	425.0	613.2	801.1	44.3	30.6
High income	1282.3	1396.1	1451.7	8.9	4.0
Sub-Saharan Africa	663.6	961.5	1268.0	44.9	31.9
East Asia and Pacific	1812.2	2020.3	2139.7	11.5	5.9
South Asia	1382.2	1692.2	1909.0	22.4	12.8
Europe and Central Asia	246.1	264.4	276.0	7.4	4.4
Middle East and North Africa	276.6	351.4	412.8	27.0	17.5
Latin America and Caribbean	439.0	521.9	579.4	18.9	11.0
Euro area	321.1	338.7	341.8	5.5	0.9

Source: World Bank, *World Development Indicators*, World Bank, Washington, DC, 2015.

TABLE 5.4 Overall Water Risk Index Framework

Physical Risk Quantity	Physical Risk Quality	Regulatory and Reputational Risk
• Baseline water stress • Inter-annual variability • Seasonal variability • Flood occurrence • Drought severity • Upstream storage • Groundwater stress	• Return flow ratio • Upstream protected land	• Media coverage • Access to water • Threatened amphibians

Source: Gassert, F. et al., Aqueduct global maps 2.1, Working Paper, World Resources Institute Washington, DC, Available online at: http://www.wri.org/publication/aqueduct-global-maps-21, 2014.

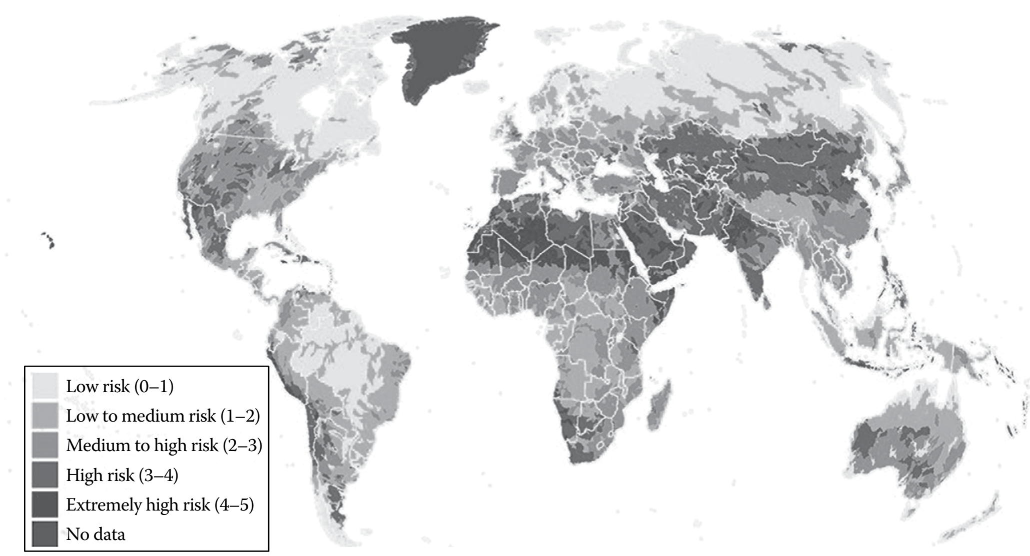

FIGURE 5.8 Overall water risk index. (From Gassert, F. et al., Aqueduct global maps 2.1, Working Paper, World Resources Institute, Washington, DC, Available online at: http://www.wri.org/publication/aqueduct-global-maps-21, 2014.)

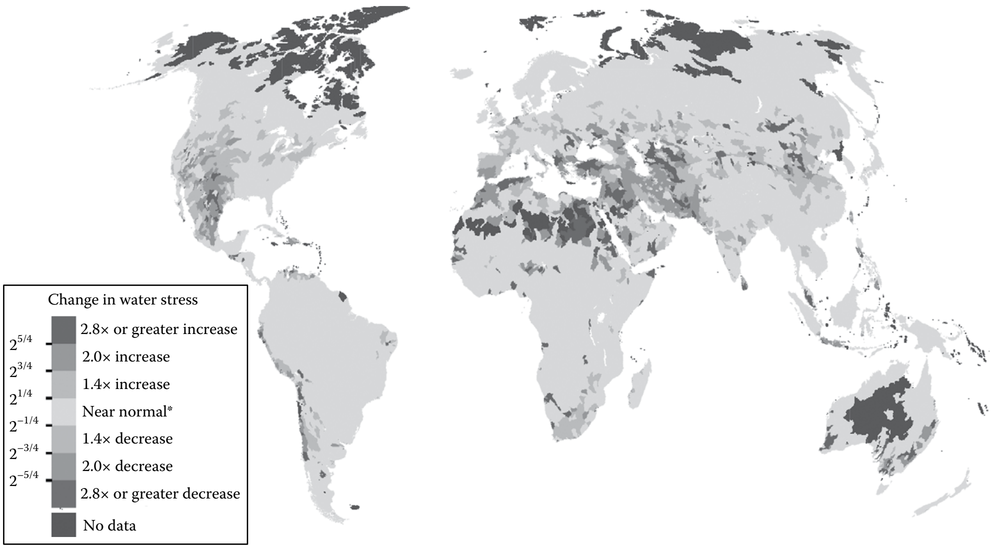

FIGURE 5.9 Projected change in water stress from baseline (1950–2010) to future (2030–2050) under business-as-usual scenario RCP8.5 SSP2. (From Luck, M. et al., Aqueduct water stress projections: Decadal projections of water supply and demand using CMIP5 GCMs, Technical Note, World Resources Institute, Washington, DC, Available online at: wri.org/publication/aqueduct-water-stress-projections, 2015.)

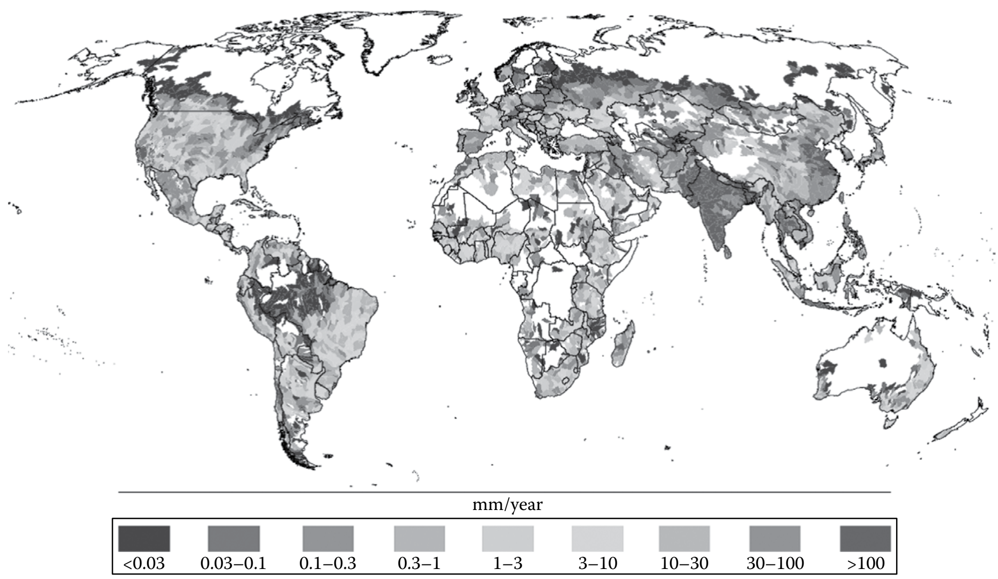

FIGURE 5.10 Agricultural water withdrawals—2010 (m^3/5 arc-min cell). (From Luck, M. et al., Aqueduct water stress projections: Decadal projections of water supply and demand using CMIP5 GCMs, Technical Note, World Resources Institute, Washington, DC, Available online at: wri.org/publication/aqueduct-water-stress-projections, 2015.)

Agriculture takes the highest share among water user sectors in low- and middle-income countries, while industry is the most important user in developed countries in temperate and humid climates (Figure 5.10). Agriculture withdraws more than 85% of water in the average African, Asian, and Pacific countries [19]. This is a very high share, which means there is a need for appropriate management. Irrigated areas have grown as much as 4–5 million hectares a year [88]. This corresponds to an average growth rate of almost 2% a year since 1960 [118]. However, this trend has declined to near 1% during the 1990s [57] and less for the last decade. This growth is justified by the productivity of irrigated agriculture: irrigated areas represent about one-sixth of arable land but provide about one-third of the world's crop production [118].

Expansion of irrigated areas occurred when crop yields also increased dramatically due to a combination of factors: improved irrigation techniques, high yield varieties, and higher rate use of fertilizers, but in arid and semiarid regions, these last improvements could only be successfully introduced in irrigated areas. However, the expansion of irrigation has been achieved with several negative environmental impacts, namely, waterlogging and salt-affected soils [57]. Arid and semiarid water-stressed areas are particularly sensitive to these detrimental effects [2]. Controlling environmental effects and increasing the performances are among the future issues for water resources management [51].

The prevailing conditions in water scarcity are worsened due to significant deterioration in water quality conditions [14]. Surface waters are becoming more polluted (low dissolved oxygen and increased fecal coliforms) in developing countries, but this trend is being reversed in high-income countries (World Bank, 1993) [139]. Problems resulting from increased salinization of aquifers are requiring increased attention in less-developed regions in arid zones [89]. Health problems are particularly acute. Each year, 900 million people are affected by diarrhea. The World Bank (1995) estimates that water supply and sanitation improvements would decrease mortality from diarrhea by 16% due to improvements in water quality, by 25% due to increased availability of water, by 37% where both improvements can be made, and by 22% where proper disposal of excreta can be effected. Several other diseases are related to water like malaria, filariasis, and bilharziasis (schistosomiasis) [11,53,101]. These problems are common in water-scarce regions and bring into clear focus the need for the availability of safe water and sanitation.

5.3 Drought Mitigation Measures

5.3.1 Basic Definitions

It is important to distinguish between aridity and drought.

Aridity is a natural permanent imbalance in the water availability consisting of low average annual precipitation, with high spatial and temporal variability, resulting in overall low moisture and low carrying capacity of the ecosystems. Aridity may be defined through climatological indices such as the Thornthwaite moisture index, the Budyko radiation index of dryness, or the UNESCO precipitation/evapotranspiration index [91,92].

Drought is a natural but temporary imbalance of water availability, consisting of a persistent lower-than-average precipitation, and has uncertain frequency, duration, and severity and unpredictable or difficult to predict occurrence, resulting in diminished water resources availability and reduced carrying capacity of the ecosystems. Many other definitions of drought exist [100,122,135]. The U.S. Weather Bureau defined drought as a lack of rainfall so great and so long continued as to affect injuriously the plant and animal life of a place and to deplete water supplies both for domestic purposes and the operation of power plants, especially in those regions where rainfall is normally sufficient for such purposes.

The interdependence between climatic, hydrologic, geologic, geomorphic, ecological, and societal variables makes it very difficult to adopt a definition that fully describes the drought phenomena and the respective impacts. Meteorologists and hydrologists have developed indices, which depend on hydrometeorological parameters or rely on probability. Several drought studies [113,122,136] give examples of these indices.

A thorough understanding of drought risks allows for informed decision-making and selection of appropriate and effective management options. Although they can be described in a variety of ways, these management options typically include a range of drought preparedness, mitigation, response, and recovery strategies.

In this context, typologies of drought risk reduction measures are defined as follows [106]:

1. Drought preparedness refers to the knowledge and capacities developed by governments, professional response and recovery organizations, communities, and individuals to effectively anticipate, respond to, and recover from the impacts of likely imminent or current drought events or conditions.
2. Drought mitigation is the lessening or limitation of the adverse impacts of droughts. Mitigation measures encompass engineering techniques as well as improved policies and public awareness.
3. Drought response is the provision of emergency services and public assistance during or immediately after a drought in order to save lives, reduce health impacts, ensure public safety, and meet the basic subsistence needs of the people affected. It can be of an immediate, short-term, or protracted duration.
4. Drought recovery refers to the restoration, and improvement where appropriate, of facilities, livelihoods, and production conditions of drought-affected communities, including efforts to reduce drought risk factors.

5.3.2 Decision Frameworks in Drought Mitigation

Droughts have significant economic, environmental, and social impacts, both direct and indirect. Many economic impacts occur in agriculture and related sectors, including forestry and fisheries, because of the reliance of these sectors on surface and subsurface water supplies. The web of impacts may become so widespread that it is often difficult to determine the accurate financial estimates of damages.

In this context, in order to structure an effective and sustainable framework for drought mitigation measures, it is important to understand the interrelationships between institutional and social parameters as defined in the following [56].

5.3.2.1 Building Institutions and Capacity for Governance

While there is strong evidence that a transition to a sustainable and equitable path is technically feasible, charting an effective and viable course for drought mitigation is not merely a technical exercise. It will involve myriad and sequential decisions among states and civil society actors. Such a process benefits from the education and empowerment of diverse actors to participate in systems of decision-making that are designed and implemented with procedural equity as a deliberate objective. This applies at the national as well as international levels, where effective governance relating to global common resources, in particular, is not yet mature. Any given approach has potential winners and losers. The political feasibility of that approach will depend strongly on the distribution of power, resources, and decision-making authority among the potential winners and losers. In a world characterized by profound disparities, procedurally equitable systems of engagement, decision-making, and governance may help enable a policy to come to equitable solutions to the sustainable development challenge and definition of effective and sustainable drought mitigation measures.

5.3.2.2 Considering Uncertainties in Possible Physical Impacts as Well as Human and Social Responses

Drought mitigation and adaptation is a risk management challenge that involves many different decision-making levels and policy choices that interact in complex and often unpredictable ways. Risks and uncertainties arise in natural, social, and technological systems. Effective risk management strategies not only consider people's values and their intuitive decision processes but also utilize formal models and decision aids for systematically addressing issues of risk and uncertainty. Research on other such complex and uncertainty-laden policy domains suggests the importance of adopting policies and measures that are robust across a variety of criteria and possible outcomes. A special challenge arises with the growing evidence that droughts may result in extreme impacts whose trigger points and outcomes are shrouded in high levels of uncertainty. A risk management strategy for drought management will then require integrating responses in mitigation with different time horizons, adaptation to an array of impacts, and even possible emergency responses in the face of extreme climate impacts. One of the central challenges in developing a risk management strategy is to have it adaptive to new information and different governing institutions.

The literature provides examples of attempts to conceptualize the different phases of water resources management in response to drought and water scarcity. These frameworks have been developed to reflect a relative emphasis on one or another element of the supply–demand balance.

Most frameworks propose a sequential or stepwise approach to water scarcity. Keller et al. [60,61] and Keller [59] suggested distinguishing three phases of river basin development: exploitation, conservation, and augmentation.

Typically, the exploitation phase would be dominated in early stages by direct surface diversion and the use of shallow groundwater, complemented, at a later stage, with progressive building of storage and water distribution, and the drilling of deep tube wells. During the conservation phase, demand management and efforts toward efficiency increase would become more important followed by more systematic water treatment and reclamation and salt disposal. The augmentation phase would focus on water transfer from distant basins and on seawater desalinization, allowing annual supply to expand beyond average annual renewable supply. While such description applies well to many of the regions that have benefited from the green revolution in the 1960s and 1970s, in particular countries like India and Pakistan, it might not be necessarily valid in other places or at other times [38].

Molden et al. [79] proposed a different series: development, utilization, and allocation, as follows:

1. *River basin development*: Dams are constructed in the most convenient locations, water resources are sufficient to satisfy demand from all sectors of the economy, and water quality and ecosystems are only affected to a minor extent. This phase is comparable to the exploitation phase as distinguished by Keller et al. [61].
2. *Utilization or conservation*: Water shortages begin to appear and competition for water emerges between the different sectors and within sectors. Water quality deteriorates and aquatic ecosystems are damaged, due to both reduced water quality and quantity. Water policies focus on improving water management and conservation, the keywords being modernization, performance, and productivity enhancement. At the same time, water pollution and groundwater withdrawals call for better and more effective regulation.
3. *Reallocation*: Water has become a rare commodity and is no longer sufficient to satisfy the aggregated demand from all sectors. Policies are directed toward the economic optimization of water, with emphasis on the reallocation of water from low value to high value uses. For this third phase, Keller et al. [61] focused on augmentation, such as through interbasin transfer or desalination, rather than reallocation.

Molle [81] pursued a more analytical approach and proposed that policy responses to scarcity should be considered in a wider political economy framework. Sequential models of basin development such as those mentioned earlier tend to be based on economic rationality or concepts of social adaptation that may be too restrictive. Societal responses to drought and water scarcity are not driven solely by economic considerations or locally perceived needs, but result from the distribution of power among stakeholders, as well as their respective interests and strategies with regard to the different options available.

Molle [81] suggested replacing the sequential approach with one that recognizes that all strategies tend to be pursued in parallel when scarcity becomes severe. In reality, it may be more useful to regard the various response options as a menu to be drawn upon according to local circumstances. Objective criteria such as benefit–cost analysis and cost-effectiveness analysis can help these decisions, but they will always be taken in a political economy framework. To complicate matters, the response options are often interdependent and come in "packages." The experience of countries taking part in the Expert Consultation shows that even though there is a broad progression from supply enhancement to demand management and reallocation as scarcity worsens, there is also a great deal of overlap, and at any one time, a range of measures are being implemented.

The EU Water Framework Directive (WFD) and EU Water Initiative water scarcity group published a policy document on "Water Scarcity Management in the Context of the WFD" [32]. This concluded that drought planning has to evolve to risk management and incorporate three primary components: a monitoring system, an impact assessment system, and a response system. It can develop into a comprehensive, long-term drought preparedness policies and plans of action, based on the following principles:

- Reducing vulnerability and increasing resilience to drought.
- Prevention in order to reduce the risk and effects of uncertainty.
- Mitigation of the adverse impacts of the hazard.
- Proactive management. Developing actions planned in advance, involving modification of infrastructures, national laws, and institutional agreements together with an improvement in public awareness.
- A drought management strategy should include sufficient capacity for contingency planning before the onset of drought. It entails effective information and early warning systems as well as effective networking and coordination between central, regional, and local authorities [128].

The EU MEDA Water project Mediterranean Drought Preparedness and Mitigation Planning (MEDROPLAN) has synthesized academic and policy aspects of drought planning and developed drought management guidelines that appealed to a broad audience, the nontechnical users, and that are especially oriented to the support of policymaking [29,67]. The main components of drought planning and management were described using six distinct features: (1) planning framework, (2) organizational component, (3) methodological component, (4) operational component, (5) public review component, and (6) examples of the application (Mediterranean Water Scarcity and Drought Work Group, [32]).

5.3.3 Policy Options

There is a key difference between responses by the state at national level and the local response of small groups or communities. These two types of responses are interdependent, but while emphasis is often placed on state policies, adjustments made by local farmers are crucial in shaping the demand for water from agriculture and its impact on the hydrological cycle. Moelle [80] introduced that elements like the nature of the state and state–citizen relationships, the impact of "shock events," the nature of the political economy, and the conditions of agrarian change are crucial in shaping the responses to water scarcity.

In this context, it is important to consider that water scarcity is perceived differently by different categories of stakeholders, who develop different adaptation and coping strategies as a function of their power and capacities.

The United States and Australia illustrate the dynamic interplay between federal and state powers as water scarcity intensifies. In the United States, water governance is primarily a state responsibility, but some federal legislation is of overriding importance, and the Endangered Species Act has become the dominant federal influence on all water withdrawals. This is a major influence on public responses to water scarcity, especially in the arid western states. In Australia, the exceptional drought of the last decade has caused the federal government to intervene and modify powers exercised by the autonomous Murray–Darling Basin Authority.

In order to capture these different dimensions of the problem, a schematic layout is presented by grouping actions in three stages: policy environment, institutional and legal framework, organization and management (Figure 5.11). The supply- and demand-side options are by and large located at the level of

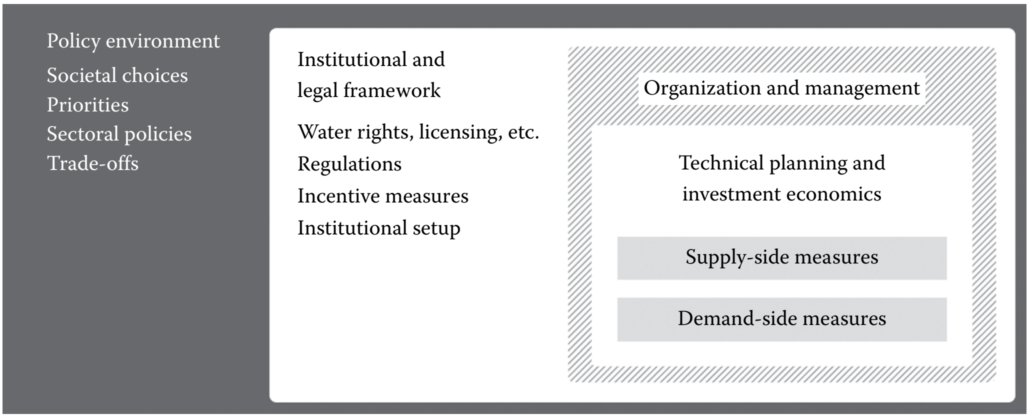

FIGURE 5.11 Structure of the policy context. (From FAO, Coping with water scarcity—An action framework for agriculture and food security, FAO, Rome, Italy, 2012, 78pp.)

TABLE 5.5 Water Scarcity Response Options by Policy Domain

Policy Domain	Supply Enhancement	Demand Management
Water	River diversion, dams, groundwater development, desalinization, pollution control	Intersectoral allocation, increase in the overall efficiency of sectoral water use
Agriculture	On-farm storage, groundwater development, reuse and recycling	Increase in crop productivity, reduction in losses, restraining the cropped area under irrigation, intrasectoral allocation (shifting to higher value production)
National food security	Food imports, storage, distribution efficiency	Reduction in waste in the food chain, changes in dietary habits

Source: FAO, Coping with water scarcity—An action framework for agriculture and food security, FAO, Rome, Italy, 2012, 78pp.

Supply enhancement includes increased access to conventional water resources through the construction of hydraulic structures aiming at regulating water supply and conveying water to the end user (dams and reservoirs, conveyance systems), as well as enhancing supply with treated wastewater, desalination, and interbasin transfers. Pollution control should also be considered a supply management option, as it increases the amount of water available for beneficial use, as well as for interbasin transfer.

Demand management, in contrast, aims to raise the overall economic efficiency of water use, or to reallocate water within and between sectors. The general aim of demand management is to maximize the benefits obtained from a given amount of water available to users, which could also include producing the same benefits from less water. In agriculture, this might involve producing more highly valued crops from irrigation, raising crop productivity, reducing the consumptive use of water by minimizing evapotranspiration, or restraining the cropped area under irrigation. Demand management options are usually more difficult and less popular to implement than supply enhancement options. This is the reason why they are often considered in a second stage, after the easier supply-side options have been implemented [80].

Improvements in the technical efficiency of distribution of water can be regarded as either a supply-side or a demand management measure, depending on the nature and scale of the action, and where responsibility lies. Major improvements to canals and pipelines, for instance, can be regarded both as supply-side measures (as they increase water available to users) and as demand-side measures (as they reduce evaporation losses and leakages), whereas local and on-farm improvements, particularly those under the control of farmers themselves, are more akin to demand management, since they affect the economic efficiency with which the water is used.

technical planning and investment economics, but they are widely influenced by the overall context of governance, institutional framework, and policy environment.

The options by major policy domain, water, agriculture, and national food security, are presented in Table 5.5. The taxonomy distinguishes between two broad categories of options: those dealing with supply enhancement and those dealing with demand management. The table sets out three domains in which supply enhancement and demand management can be applied. First, there is water in its broadest sense, with development and management of the resource to the benefit of users in all sectors, including the environment. Second, there is agriculture—a major water user. Finally, there is the realm of food self-sufficiency and national food security, with implications for a country's international trade as well as consumption habits and the organization of its food industry.

5.3.4 Responses to Policy Initiatives

The time sequence of responses to the growth of water scarcity, which can be observed in many regions, is illustrated in Figure 5.12.

In early stages of water development, when water supply can easily satisfy demand, priority is usually given to supply management through the construction of storage and conveyance infrastructure in support of irrigation development. Later, when the supply of water no longer satisfies unrestricted demand and the low-cost gains in efficiency have already been made, efforts focus on demand management, in which the overall economic efficiency of water use is addressed. In agriculture, this can be done through better crop and water management and the modernization of irrigation infrastructure. Over time, measures to enhance supply through the more systematic reuse of wastewater also become important. As demand is increasingly limited by available supply, allocation policies become more prominent. National food security may have to be modified to allow more imports of agricultural products, where there is not enough water for agricultural self-sufficiency [49]. Eventually, other, more costly, forms of supply enhancement, for example, desalination, may become feasible. Loeve et al. [70] stated that the pressure will mount on agriculture to increase its water productivity not only through more technically efficient use of water but also through a shift toward higher value crops in order to optimize the economic return from irrigation water.

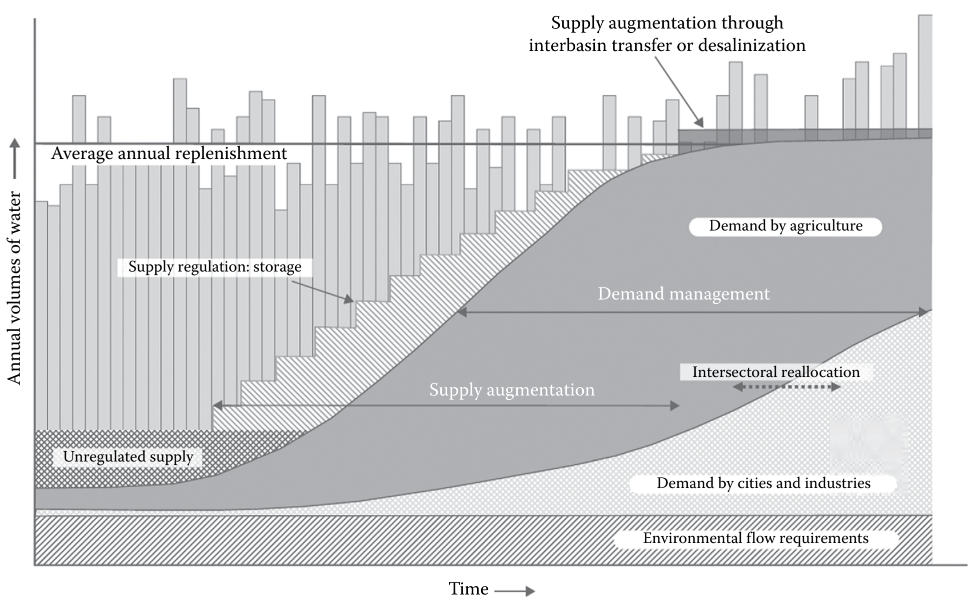

FIGURE 5.12 Coping with water scarcity: A stylized sequence of the relative demand for water by different sectors and response options over time. (From FAO, Coping with water scarcity—An action framework for agriculture and food security, FAO, Rome, Italy, 2012, 78pp.)

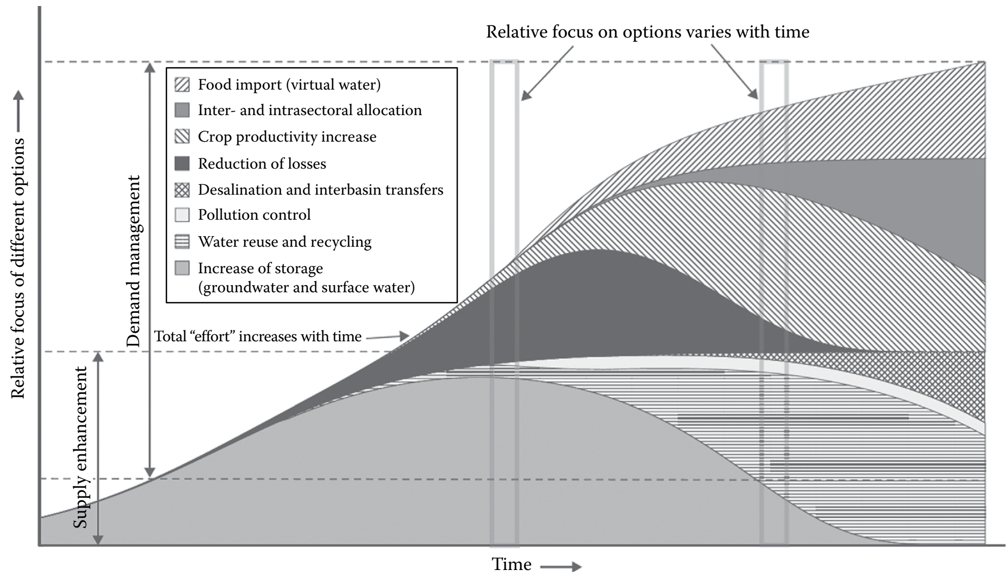

FIGURE 5.13 A schematic representation of the relative focus on different options for the agricultural sector to cope with increasing levels of water scarcity over time. (From FAO, Coping with water scarcity—An action framework for agriculture and food security, FAO, Rome, Italy, 2012, 78pp.)

The relative distribution of focus on different supply and demand options over time is shown in Figure 5.13. Clearly, the shape of the curves, the sequencing of the options, and the relative importance and relevance of the different options will vary according to prevailing agroclimatic, socioeconomic, and market conditions as well as the policies and strategies chosen. It is important to note that this is neither an "optimal" bundle and sequence of measures nor a model to follow in every case. Rather, its purpose is to illustrate the variety of options available and the way they might evolve over time.

One eventual outcome of increased competition for scarce water resources, of relevance to national food security, is when agriculture is no longer able to satisfy national demand and additional demand for agricultural products (including food) must be met through imports. Importing agricultural produce in a water context is often referred to as importing "virtual water." According to Molle [81], importing virtual water can be considered as the ultimate case of supply management since the amount of water available is "augmented" by the amount embodied in imports, which would otherwise be withdrawn by agriculture. From another viewpoint, at a macroeconomic level, the import of virtual water is an efficiency gain since the water that would otherwise be used in agriculture is released for potentially more productive use, and therefore, it can be considered as a demand management measure [50].

5.4 Drought Management Strategies

5.4.1 Basic Principles

The different roles, attitudes, and strategies of the various stakeholders involved in water policy and management need to be clearly understood. Table 5.6 shows the objectives of major groups of decision-makers at different levels and the strategies at their disposal to implement drought management strategies and address water scarcity. The objectives of specific groups may be misaligned or even conflicting. To avoid this danger, the policies of different sectors need to be harmonized (especially between agriculture, water resources, and the environment), and the private incentives influencing farmers should

TABLE 5.6 Strategies and Policies for Coping with Water Scarcity According to Categories of Decision-Makers

Level	Supply Side	Demand Side
What: Objective		
National water authority	Providing safe and sufficient water to all sectors of the economy while maintaining the integrity of the resource base	Ensuring efficient and sustainable use of freshwater
National authority for agriculture and irrigation	Securing sufficient water supply to satisfy the needs of the agriculture sector	Ensuring highest productivity of water used in agriculture
River basin or aquifer authority	Ensuring that available supply of water is provided to all users in a transparent, reliable, and effective way	Ensuring efficient and sustainable use of freshwater by all users at river basin or aquifer level, avoiding conflicts and ensuring environmental protection
Irrigation scheme manager, water user association	Ensuring that a sufficient supply of water is provided to all users in a reliable, timely, and effective manner	Ensuring that available water is used in the most productive way
Farmers	Securing supply of water for all farm operations	Using available water most productively and profitably
How: Strategies and policies		
National water authority	Construction of multipurpose dams, desalination plants, interbasin transfer, pollution control, negotiation of transboundary allocations, establishment and enforcement of environmental flows	Adaption of water laws, development of water institutions, tighter enforcement, promotion of water markets, trade mechanisms, water charges or quota mechanisms, administration of water rights, water allocation and water quality standards, public awareness campaigns, buyback for environmental purposes
National authority for agriculture and irrigation	Construction of irrigation dams, negotiation of water allocation to agriculture	Incentives for irrigation modernization, adoption of service-oriented management of irrigation, adaptation of irrigation infrastructure for increased flexibility and reliability of water supply, review of agricultural water tariff policy
River basin or aquifer authority	Construction of large dams, dam operation rules, aquifer recharge, well drilling (groundwater development)	Optimization of dam management, management of water allocation mechanisms, administration of groundwater use, pollution control
Irrigation scheme manager; water user association	Negotiation of water allocation, recycling of drainage water, collective land improvements, on-scheme storage development and management	Reducing losses in distribution, incentives for increased economic efficiency of field-level water use (subsidies, volumetric pricing, water markets)
Farmers	Individual well drilling, reuse of drainage water, on-farm water conservation investments, on-farm water storage, trading water, scavenging water, collective action	On-farm efficiency improvement (pressurized irrigation), deficit irrigation, adaptation of crops and crop varieties to water supply conditions

Source: FAO, Coping with water scarcity—An action framework for agriculture and food security, FAO, Rome, Italy, 2012, 78pp.

be aligned with the overriding public purpose of optimizing water use. The same applies to the different parties at all levels of water management.

5.4.2 Policy Actions

Policies are frequently assessed according to four criteria:

1. *Environmental effectiveness*—Whether policies achieve intended goals in reducing emissions or other pressures on the environment or in improving measured environmental quality.
2. *Economic effectiveness*—The impact of policies on the overall economy. This criterion includes the concept of economic efficiency, the principle of maximizing net economic benefits. Economic welfare also includes the concept of cost-effectiveness and the principle of attaining a given level of environmental performance at lowest aggregate cost.
3. *Distributional and social impacts*—Also known as "distributional equity," this criterion concerns the allocation of costs and benefits of policies to different groups and sectors within and across economies over time. It includes, often, a special focus on impacts on the least well-off members of societies within countries and around the world.
4. *Institutional and political feasibility*—Whether policies can be implemented in light of available institutional capacity, the political constraints that government's face, and other factors that are essential to making a policy viable.

All criteria can be applied with regard to the immediate "static" impacts of policies and from a long-run "dynamic" perspective that accounts for the many adjustments in the economic, social, and political systems.

Criteria may be mutually reinforcing, but there may also be conflicts or trade-offs among them. Policies designed for maximum environmental effectiveness or economic performance may fare less well on other criteria, for example. Such trade-offs arise at multiple levels of governing systems. For example, it may be necessary to design international agreements with flexibility so that it is feasible for a large number of diverse countries to accept them, but excessive flexibility may undermine incentives to invest in cost-effective long-term solutions.

5.4.2.1 Policy Makers Make Use of Many Different Policy Instruments at the Same Time

Theory can provide some guidance on the normative advantages and disadvantages of alternative policy instruments in light of the criteria discussed earlier. The range of different policy instruments includes the following:

- Economic incentives, such as taxes, tradable allowances, fines, and subsidies
- Direct regulatory approaches, such as technology or performance standards
- Information programs, such as labeling and energy audits
- Government provision, for example, of new technologies or in state enterprises
- Voluntary actions, initiated by governments, firms, and nongovernmental organizations

The diversity in policy goals and instruments highlights differences in how sectors and countries are organized economically and politically as well as the multilevel nature of mitigation: The success of management strategies and mitigation measures depends in part on the presence of institutions capable of designing and implementing regulatory policies and the willingness of respective publics to accept these policies. Many policies have effects, sometimes unanticipated, across multiple jurisdictions—across cities, regions, and countries—because the economic effects of policies and the technological options are not contained within a single jurisdiction.

There are a growing number of countries devising policies for adaptation, as well as mitigation, and there may be benefits to considering the two within a common policy framework: Traditionally, policy design, implementation, and evaluation have focused on governments as central designers and implementers of policies, but new studies have emerged on government acting in a coordinating role.

In these cases, governments themselves seek to advance voluntary approaches, especially when traditional forms of regulation are thought to be inadequate or the best choices of policy instruments and goals are not yet apparent.

The successful implementation of policy depends on many factors associated with human and institutional behavior: One of the challenges in designing effective instruments is that the activities that a policy is intended to affect are also influenced by social norms, decision-making rules, behavioral biases, and institutional processes. Additionally, the norms that guide acceptable practices could have profound impacts on the baselines against which policy interventions are evaluated, either magnifying or reducing the required level of policy intervention.

5.4.3 Regional Initiatives

Farmers are typically very adaptable to changes in market opportunities and access to productive inputs including water. The successful response of agriculture to fast population increase in the second half of the last century and to progressive shortage of land and water is a case in point: over the past 30 years, the world's total agricultural production doubled, while the expansion of cultivated land was only about 15%, and all of this growth occurred in land equipped for irrigation. In regions of land scarcity, such as South Asia, the growth in commodity production was almost completely based on increases in yields and cropping intensities. In contrast, in South America, the pressure on land is less, and 40% of the growth in production was due to an aerial increase in farmed land. Adaptation is evident in water-scarce regions such as the Near East and North Africa, where irrigation efficiencies are often 20% higher than in water-rich areas of Southeast Asia, Latin America, or sub-Saharan Africa.

5.4.3.1 Middle East and North Africa

Some countries have already taken steps to set up drought mitigation systems. Morocco has established the National Drought Observatory within the King Hassan II Institute in Rabat. In Syria, an Early Warning Unit for Drought is being established within the Ministry of Agriculture and Agrarian Reform through an FAO Technical Assistance Project [103]. FAO is assisting Jordan in developing strategies and an action plan for drought mitigation through a Technical Cooperation Program (TCP) project. In addition, the World Food Program is planning to establish a Drought Early Warning Unit within the National Agricultural Research Centre of the Ministry of Agriculture [36].

Water governance in many Arab states has traditionally taken place at the local level. Oasis communities in many areas continue to allocate water among individuals, and quality is maintained through resource ownership responsibilities [137]. Informal irrigator councils around the springs in Mount Lebanon still govern the resource without government intervention. In the twentieth-century drive toward developing supply and irrigation, new institutional structures emerged to manage the nation's water resources.

Until recently, water management in the Arab region was highly centralized and managed mostly at the national level with little local stakeholder or civil society participation, resulting in ineffective, fragmented structures. Water responsibilities were scattered among government departments, bureaucracy and inefficiency influenced decision-making, and action was slow and nontransparent. Various actors had their own roles, rights, and responsibilities, with often conflicting interests in managing water resources [66,90].

Local community stakeholders and user associations are established in Egypt, Jordan, Lebanon, Libya, Morocco, Oman [138], Tunisia, and Yemen. The Arab region's recent experience shows that some of the water user associations have been established through a bottom–up consultative approach, where authorities have conferred with ordinary water users. This helps to bolster participation, improve farmer welfare, and develop irrigation and drainage by providing an alternative to public utility monopolies [1].

Some field applications representing good practices include the following:

- *Pioneering water user associations in Lebanon: The Association of the Friends of Ibrahim Abd El Al*: The pilot project was funded by the Lebanese Recovery Fund, under the management of the United Nations Development Program and in partnership with the Litani River Authority. This project sets the infrastructure for the distribution network, shows the advantages and efficiency of modern irrigation techniques, proposes new cropping patterns in the region with their socioeconomic impact, and supports the establishment of water user associations [102].
- *Jordan water conservation education*: In 1986, Jordan's Royal Society for the Conservation of Nature (RSCN) introduced environmental conservation clubs in single-gender primary and secondary schools throughout the country. The water conservation curriculum for secondary school eco-clubs demonstrated several important results:
  - *Professional development*: Skill building for staff members of RSCN's education department was a major component of this project.
  - *Dialogue about water conservation*: The new curriculum helped to open a public dialogue on water conservation.
  - *Introduction of interactive teaching methods*: The curriculum introduced Jordanian teachers to interactive teaching, which contrasted sharply with their traditional lecture-based methods [109].
- *Heroes of the UAE*: A national press campaign jointly developed by the Emirates Wildlife Society in association with the WWF and the Environment Agency—Abu Dhabi and endorsed by the Ministry of Energy, the Ministry of Environment and Water, Masdar City, and the Abu Dhabi Water and Electricity Authority. This campaign aims to raise awareness of the importance of rationing energy consumption to avoid shortages. The campaign involved the press and outdoor and radio advertising in early 2009, as well as a website (www.heroesoftheuae.ae). Information was made available to everybody to learn more about the problem's causes and also find out what they can do to help reduce energy consumption [52].

5.4.3.2 Sub-Saharan Africa

In sub-Saharan Africa, various forms of short-term and long-term measures have been enacted [107,108].

5.4.3.2.1 Short-Term Measures

Government interventions: A number of short-term interventions have been used by governments to ameliorate the effects of droughts. Interventions included food handouts (including child supplementary feeding and school feeding), food for work, crop packs, livestock schemes, tillage support, and emergency rural and urban water assistance.

Food handouts: Direct food handouts have been the most common type of government intervention throughout the South African Development Community (SADC).

Food for work: Food-for-work programs have been used extensively in many countries in the region, partly because of their performance in self-targeting.

Crop packs: Crop packs are a short-term government intervention to rehabilitate smallholder farm families affected by drought.

Livestock schemes: Livestock support schemes have taken a variety of forms, from distribution of free livestock inputs such as mineral licks in Swaziland to construction of permanent livestock holding pens and feedlots for supplementary feeding during critical months in Zimbabwe. In Botswana, livestock relief schemes have normally included free vaccinations, an expanded livestock water development program, ensured availability of livestock feeds and other requisites, and (where feasible) incentives for increased removal of livestock.

Emergency urban and rural water assistance: Water crisis conditions in the past have seen many governments supplementing rural (and urban) water by providing emergency water supplies through mobile water tanks and the construction of boreholes in rural areas. A number of problems, however, were faced under such programs. First, boreholes and water tanks were too few to prevent women from walking long distances to fetch water. Second, the quality of water from the tank was not always guaranteed. Third, although construction of boreholes could have constituted a long-term intervention, inadequate planning for the management and maintenance of borehole pumps led to frequent breakdowns or total collapse of some borehole water points. Fourth, because of pressure from the water crisis and the more-or-less ad hoc drilling, some boreholes were drilled where the water table had already fallen.

5.4.3.2.2 Long-Term Measures

Support for small agricultural development: Drought recovery programs for the smallholder sector in some countries have a long-term component. Examples are the livestock water development program of Botswana and the female calf-heifer loan scheme in Zimbabwe, which includes medication and veterinary services and also risk insurance.

Poverty alleviation programs: Various initiatives have been started in many countries to tackle poverty. Considerable progress has been made, and some countries now have poverty alleviation action plans drawn up. However, progress in the implementation of these plans has been much slower.

Maintenance of strategic reserves: Maintenance of a financial reserve facility to complement a physical strategic grain reserve has become a popular longer-term risk management measure in some countries in the region.

Macroeconomic liberalization: Most SADC countries have embarked on macroeconomic adjustment programs that are aimed at restoring their economies to the growth path by encouraging greater efficiency in use of scarce resources.

Research: Many governments in the region are also reexamining the role water-saving technologies can play in alleviating drought-related water shortages. In some countries (e.g., Mauritius), research into alternative irrigation systems and more drought-tolerant crop varieties (e.g., for sugarcane) is being reinforced as a long-term strategy for drought mitigation.

Nongovernment interventions: The most common type of long-term nongovernment intervention to mitigate drought effects has been risk insurance, which farmers have increasingly relied on, particularly those in the large-scale sector. Another area of interest to the private sector is research into water-saving technologies (both in terms of irrigation systems and crop varieties).

One of the most important drought preparedness measures for the region is SADC Regional Early Warning System (REWS) that provides member states and the international community with advance information on food security prospects in the region. The REWS, a project within the Food Security Technical and Administrative Unit, comprises a Regional Early Warning Unit based in Harare and autonomous National Early Warning Units in each of the SADC member states. The regional and national units provide early warning and food security information on the following:

- Food crop performance, especially providing alerts in case of crop failures, and other factors affecting food supplies
- Food supply and demand assessments and projections, including imports and exports
- Food-insecure areas and the populations involved

Another example is the Great Green Wall. The initial idea of a line of trees from east to west through the African desert— a Great Green Wall—evolved into a series of interventions addressing the challenges of the people in the Sahel and the Sahara. The overall goal of this African Union initiative supported by FAO is to support local communities in the sustainable management and use of their forests, angelands, and other natural resources. The Great Green Wall Initiative seeks to improve the food security of local populations, while contributing to climate change mitigation and adaptation.

5.4.3.3 Europe

The development of a drought monitoring and early warning system is critical for assessing drought conditions, communicating threats, and triggering actions in a systematic and efficient manner as drought conditions intensify.

In the region, the European Commission's Joint Research Centre has developed a European Drought Observatory (EDO) for assessing, monitoring, and forecasting droughts at European level. Also, interoperability arrangements have been established with key data centers at European, regional, and local levels. In southeastern Europe, Slovenia was selected by the eleven-country region to host the Drought Management Centre for Southeastern Europe (DMCSEE) with support from the UNCCD Secretariat in cooperation with the World Meteorological Organization (WMO) [31].

The EDO and the DMCSEE provide a Europe-wide picture of the occurrence, severity, extent, and duration of droughts, including direct access to information by national, regional, and local services. As reported by the European Commission [28], drought indicators are available for precipitation, soil moisture, vegetation response, and a combined indicator targeted at agricultural droughts. However, further efforts are required to test and improve the indicator set and to add more data from national and river basin levels.

In the framework of the EU/FAO Improved Global Governance for Hunger Reduction Programme, FAO has developed the Agriculture Stress Index System (ASIS) to detect agricultural areas, at global level, that have a high likelihood of water stress (drought). Based on Earth Observations, ASIS could support the agricultural drought monitoring activities of the region (see www.fao.org/climatechange/asis/en/).

EU has a range of policies relating to water scarcity and droughts. The primary water management policy is the WFD. It is essential that River Basin Management Plans include a detailed analysis of water use and its impacts on availability and actions are identified within the programs of measures required. These must also take account climate change impacts. Drought management plans could be included within this approach.

While considerable information is available on water scarcity and droughts at an EU level, there are significant constraints, such as river basin–based information and the lack of common definitions of issues such as "drought" across the member states. The Commission has identified these problems and developed Water Information System for Europe (WISE) information system, which is providing a platform for improved information. WISE is a partnership between the European Commission (DG Environment, Joint Research Centre and Eurostat) and the European Environment Agency, known as "the Group of Four."

WISE addresses several user groups:

- EU institutions as well as member states' national, regional, and local administrations working in water policy development or implementation
- Professionals working in the water field from public or private organizations, with a technical interest on water
- Scientists working in the water field
- General public, including in this group those working in private or public entities not directly related to water policy but with an indirect interest in water (regular or sporadic)

Neighboring countries to the EU also experience major water scarcity and drought problems. The EU Water Initiative is a major step forward in bringing together support on water management for these countries. Much of the support on infrastructure is related to water quality, while water resource issues are often addressed through policy and governance support [43].

Some of the most relevant research projects completed using EU grants schemes for water scarcity and drought are listed in the following because they have facilitated the development and/or identification of good practices:

Project: AQUASTRESS (http://www.aquastress.net)

Field: Agriculture

Title: Mitigation of Water Stress through New Approaches to Integrating Management, Technical, Economic and Institutional Instruments

Summary: The project delivered interdisciplinary methodologies enabling actors at different levels of involvement and at different stages of planning process to mitigate water stress problems. The project drew on both academic and practitioner skills to generate knowledge in technological, operational management, policy, socioeconomic, and environmental domains. Contributions came from 35 renowned organizations, including SMEs, from 17 countries. The project generated scientific innovations to improve the understanding of water stress from an integrated multisectoral perspective to support diagnosis and characterization of sources and causes of water stress and assessment of the effectiveness of water stress management measures and development of new tailored options.

Project: FLOWAID (http://www.flow-aid.wur.nl/UK)

Field: Efficiency in Agriculture

Title: Farm Level Optimal Water Management: Assistant for Irrigation under Deficit

Summary: The project aimed to develop and test a sensor technology for irrigation under deficit conditions that could be used at farm level in a large variety of setups and constraints. A water management decision support system (DSS) was also developed to assist in farm zoning and crop planning, in relation to expected water availability, according to basin management. These tools were evaluated at pilot sites in four Mediterranean countries, Italy, Turkey, Lebanon, and Jordan, as well as the Netherlands, chosen in order to differ in the sort of constraints, irrigation structures, crop types, local water supplies, availability of water and water sources, amount and quality, local goals, and complexity.

Project: RECLAIM WATER (http://cordis.europa.eu/result/rcn/46853_en.html)

Field: Reuse/Groundwater Recharge

Title: Water Reclamation Technologies for Safe Artificial Groundwater Recharge

Summary: The strategic objective of the project was to develop hazard mitigation technologies for water reclamation providing safe and cost-effective routes for managed aquifer recharge. The work assessed different treatment applications in terms of behavior of key microbial and chemical contaminants. The knowledge generated in the project and technologies developed were also suited to the needs of developing countries, which have a growing need of supplementation of freshwater resources. The project integrated technological water reclamation solutions with natural attenuation processes occurring in the subsurface to achieve upgraded water quality assessed on the basis of key contaminants.

Project: NEWATER (http://www.newater.info/)

Field: Integrated Water Resources Management

Title: Approaches to Adaptive Water Management under Uncertainty

Summary: Adaptive Water Management (AWM) is a management approach that takes the complex socioecological nature of river basin environments into account in policy development and implementation. AWM addresses the inherent uncertainties associated with management and complexity by increasing and sustaining the capacity to learn while managing. NeWater studied and fostered AWM as a concept guiding theory and practice. Taking up the interdisciplinary challenge of managing river basins as socioecological systems, NeWater reflected the diversity of perspectives and potential through 37 project partners from Europe, Africa, and Central Asia. The project supported capacity building of stakeholders in seven different case study basins (Europe, Guadiana, Rhine, Elbe, and Tisza Basins; Africa, Orange and the Nile Basin; Asia, Amudarya Basin) as well.

Project: GABARDINE (http://cordis.europa.eu/result/rcn/51970_en.html)

Field: Reuse/Groundwater Recharge

Title: Groundwater Artificial Recharge Based on Alternative Sources of Water: Advanced Integrated Technologies and Management

Summary: The theoretical background, technologies, methodologies, guidelines, mathematical tools, platforms, and decision support elements developed in the project were implemented at all test sites and intensively disseminated in order to promote worldwide application of acquired knowledge. The new concepts of vulnerability and impact assessment, the innovative groundwater simulation tool, the knowledge base platform, and the DSS, among other research products, offered efficient support to planning and management to various potential end users, such as water supply companies or governmental agencies, in order to contribute to the achievement of the overall water resources management objectives as well as water resources and policy development.

Project: MEDINA (http://cordis.europa.eu/project/rcn/81392_en.html)

Field: Alternative Water Resource: Desalination

Title: Membrane-Based Desalination: An Integrated Approach

Summary: Project consisted of an innovative approach based on integration of different membrane operations in pretreatment and posttreatment stages. The main objectives were (1) to develop analytical methods for appropriate indicators, prediction tools, procedures, and protocols at full-scale desalination facilities, (2) to identify seawater pretreatment strategies by designing advanced hybrid membrane processes, (3) to optimize RO membrane module configuration, (4) to develop strategies to approach the concept of Zero Liquid Discharge, and (5) to increase the sustainability of desalination process by reducing its energy consumption rate.

Project: WATCH (http://www.eu-watch.org/nl/25222705-Home.html)

Field: Climate Prediction

Title: Water and Global Change

Summary: WATCH developed new methods to obtain relevant information (means, extremes, and uncertainties) from global datasets and climate model outputs. The final product drove the combination of this new hydroclimatological approach of assessing floods and droughts in the twenty-first century with assessments of human and ecological water demands. The products addressed to policymakers included the following: (1) Finalized scenarios that will provide a picture of how agricultural and domestic water use impacts the global water cycle for the past, present, and future scenarios; (2) maps identifying regions where hydrological situation is significantly impacted by climate change in terms of, for example, precipitation, soil moisture, and river discharge; (3) space time development and propagation of drought: (a) comparison of selected river basins and (b) regions; (4) a picture of the location and strength of global feedback hotspots across the globe, creating a new correction map to allow feedbacks to be supplied into the water resources analysis; and (5) consequences of changing water availability for drinking water, industry, and (hydro) energy.

Project: CIRCE (http://edgar.jrc.ec.europa.eu/FP6-project.php)

Field: Climate Prediction

Title: Climate Change and Impact Research: The Mediterranean Environment

Summary: The major contributions of the project were as follows: four emission scenarios of greenhouse gas and air pollutants for the years 2000, 2010, 2025, and 2050, ranging from no global action on climate change and air pollution to a global climate policy. To evaluate as to what extent the EU27 countries are able to improve the environmental situation in the Mediterranean domain, the BAP scenario explores strict EU27 air pollution measures and the CAP scenario explores the effect of combined EU27 climate and air pollution policies.

Project: XEROCHORE (*http://www.feem-project.net/xerochore/*)

Field: Drought Policy

Title: Exercise to Assess Research Needs and Policy Choices in Areas of Drought

Summary: The project consisted of a Support Action aimed to assist the development of a European Drought Policy in accordance with the EU WFD. Objectives included the following: (1) a state-of-the-art review and identification of the research gaps in the natural system, in impact assessment, in policymaking, and in integrated water resources management and (2) an assessment of the possible impacts of droughts and guidance on appropriate responses for stakeholders. Project produced a set of five science-policy briefs in support of policymaking in the field of drought management. Science-policy briefs addressed articles 5, 8, 9, 11, and 13 of the WFD and briefly described limitations identified with regard to drought management and recommendations for improving drought preparedness and mitigation.

Project: MIRAGE (http://cordis.europa.eu/project/rcn/89399_en.html)

Field: Drought Policy

Title: Mediterranean Intermittent River Management

Summary: The implementation of EU WFD in catchments with temporary rivers presents a significant challenge for watershed managers. The MIRAGE project, for the first time, comprehensively investigated the applicability of specific management options under the characteristic flush and drought conditions of temporary streams. Through investigations in seven basins, MIRAGE provided a framework for managing many Mediterranean water bodies dominated by temporary waters. MIRAGE deployed a multiscale approach to improve the understanding of temporary river responses to hydrologic, biogeochemical, and sediment transport events.

Project: MEDROPLAN (http://www.iamz.ciheam.org/medroplan/)

Field: Drought Policy

Title: Mediterranean Drought Preparedness and Mitigation Planning

Summary: Drought Management Guidelines, which were published as a result of the MEDROPLAN project, are a "manual" that provide an effective and systematic approach to the development of drought management plans based on the existing scientific and technical knowledge and adapted to the socioeconomic, political, and environmental conditions.

Project: ACQWA (http://www.acqwa.ch/)

Field: Impacts of Climate Change

Title: Assessing Climate Impacts on the Quantity and Quality of Water

Summary: The goal of the project was to use advanced modeling techniques to quantify the influence of climatic change on major determinants of river discharge at various time and space scales and analyze their impacts on the society and economy, also accounting for feedback mechanisms.

5.4.3.4 Central Asia

In Central Asia, as reported by FAO [41], upgrading hydrometeorological monitoring services and improved information sharing is a priority throughout the region. Central Asian countries already have in place a system for managing water in the basins under drought conditions, but earlier and systematic information sharing would permit more effective planning and drought mitigation measures. There is a legacy of national hydrometeorological networks and related scientific capacity that are, in general, sufficiently functional to allow countries monitor broad trends pertinent to climate as well as to trigger the declaration of drought emergencies and response strategies. However, there is a need to improve the instrumentation of old hydrometeorological networks (river and rainfall gauges) within countries, enable access to available hydrometeorological data by potential users, and increase cooperation between countries on improving drought monitoring and early warning systems.

In addition to improving early warning systems, Tajikistan priorities include a rebalancing of public expenditure support and policy away from large-scale irrigation and cotton and toward measures that conserve water in both irrigated and rainfed lands and community-based watershed management measures that support these programs. Uzbekistan has largely maintained the central structure and institutional arrangements inherited from the Soviet period. Its hydrological and meteorological systems as well as coordination logistics remain largely intact. Investment programs are ongoing to restore delta ecosystems in the drought-prone north and to improve drinking water supply systems there. However, a mix of policy reform and rehabilitation of drainage and irrigation systems to improve irrigation water management and conservation will have the highest impact, together with greater community outreach and involvement in drought planning and mitigation measures. Kazakhstan has prepared a national drought planning and mitigation strategy with the participation of a range of stakeholders. It also has an effective emergency intervention system. Improved natural resource management, including measures to address desertification and restore degraded pasture and forest, together with improved water management, is planned for, and substantial investments have already begun [27,129]. The challenge will be to involve local communities as the main stakeholders in the planning and implementation of such programs.

Although Kyrgyzstan is not water scarce, it has to conserve water in order to serve the lower riparian countries in an equitable way. Therefore, the modernization of irrigation systems is important, as well as the development of sustainable water user associations that can manage water in an efficient way. The priority is strengthening the Ministry of Ecology and Emergencies to work with other agencies, local government, and communities in developing planning and mitigation measures and improving pasture management strategies. Turkmenistan has over 97% of its cropped area dependent on irrigation; the priority is improved management of irrigation and drainage water through policy, rehabilitation, and infrastructure improvement measures. Turkmenistan also needs to concentrate some of its efforts in maintaining its marginal grasslands and prevent further erosion and desertification. More adapted crops and cropping patterns should also be introduced to improve the productivity of irrigated areas [129].

To achieve the established goal of adopting drought management strategies in the Near East Region, member countries are called upon to

1. Enact legislation and policies for establishing relevant national enabling mechanisms for drought mitigation preparedness strategies
2. Create the required institutional setup for planning, implementing, coordinating, and monitoring the national programs for drought mitigation
3. Provide the necessary resources to establish a drought watch and early warning system to assure timely alerts and preparedness at country level
4. Establish adequate liaison with regional and international organizations for following up drought mitigation activities at national, regional, and global levels
5. Accord due attention to the socioeconomic dimension of drought, within the framework of comprehensive and integrated preparedness and mitigation plans, and address rehabilitation and development, including water resources, rangeland, livestock, forestry, and crop production
6. Focus on the water demand management approach and consider efficiency of water use as the basis for drought mitigation
7. Increase investment in agricultural research to improve water use efficiency and crop production under water shortage conditions and to develop drought and salt-tolerant varieties
8. Support established to the Regional Network on Drought Management for the Near East and North Africa
9. Promote regional cooperation and exchange of experiences among member countries [36]

5.4.3.5 Mediterranean

In the Mediterranean, risks of water shortage are generally ascribable to high level and growth of demand despite limited renewable water resources—and mainly irregular and unequal qualities—thus with availabilities that rarefy [74].

In this context, a strategic project, MEDROPLAN, provided the basis for a structured approach to develop and publish Drought Management Guidelines and Strategies. These set of guidelines and strategies provided an integrated approach to face droughts from a risk management perspective that

- Minimizes the impacts of drought in the population and the resources
- Includes the physical and socioeconomic characteristics of Mediterranean countries
- Responds to the actual situation of institutional and civil stakeholders

The guidelines provide an effective and systematic approach to develop drought management plans and strategies based on existing scientific and technical knowledge and adapted to the socioeconomic, political, and environmental conditions. The proposed approaches can be applied not only in the Mediterranean region but also in other regions of the world suffering from drought. The guidelines are not prescriptive and have to be taken as a reference, and the tools proposed have to be chosen and adapted to the planning reality. The guidelines are formed through strategic integration of the following components:

The *planning framework* defines the local, regional, and national context for developing drought planning options and strategies. The planning framework guides stakeholders define the planning purpose and processes.

The *organizational component* assists stakeholders understand institutional and legal framework within which the drought plan is designed and implemented as well as to define an organizational structure to implement the plan in an efficient manner. It also emphasizes the geographical unit of planning, with respect to which planning tools to prevent and mitigate drought-induced water shortage have to be chosen.

The *methodological component* presents a scientific approach to risk evaluation through the following steps:

Compile and provide the most comprehensive technical and scientific approaches to drought characterization and development of indicators of risk in water resources and agricultural systems

Define the methods used for risk management in the context of the Mediterranean region

Define the academic methods for evaluating social vulnerability based on the indicators that include the capacity to anticipate, cope with, and respond to drought

Encourage technical studies to strengthen use of indices and declaration of drought

The *operational component* identifies both the long- and short-term actions that can be implemented to prevent and mitigate drought impacts. The activities and actions are essential for the creation of specific drought planning and response efforts. The operational component includes five aspects:

Preparedness and early warning (permanent measures)

Establishing priorities to be respected during water shortages due to droughts

Thresholds defined by drought indices and indicators (physical and social)

Defining the actions

Evaluating the process to implement the actions

The *public review component* presents a methodology to revise the application of the previous components when developing a drought plan. It requires a public multistakeholder dialogue and includes a protocol for developing dialogue workshops, guided interviews, and questionnaires aiming to collect feedbacks. Dissemination of information is also essential in this component. Apart from the initial public review, it is important to make periodic revisions of the drought plan, especially after drought episodes, in order to make the necessary adjustments in the light of the results of the application of the plan and of changes in society, technology, and the environment.

5.4.3.5.1 Some Good Examples of Actions

In France, wastewater reuse has become a part of regional water resources management policies. It is practiced mostly in the southern part of the country and in coastal areas, compensating local water deficiencies. In Portugal, it is estimated that the volume of treated wastewater is around 10% of the water demand for irrigation in dry years and that between 35,000 and 100,000 ha could be irrigated with treated wastewater. In Spain, the total volume of wastewater reclaimed amounts to 0.23 km^3/year, being used mainly for irrigation in agriculture (89%), recreational areas and golf courses (6%), municipal use (2%), environmental uses (2%), and industry (1%).

Turkey is part of a regional initiative with policy relevance, Agricultural Member States Modeling (AGMEMOD). It is used by member states of the EU to enable quantitative assessment of the potential impacts on the agricultural commodity markets. AGMEMOD is an econometric, dynamic, partial equilibrium, multicountry, multimarket model. A study was undertaken by the EC Joint Research Centre [33] to develop a detailed dataset and modeling structure for the main agricultural commodities in Turkey and integrating this Turkish AGMEMOD submodel into the overall AGMEMOD modeling framework. As part of this study, a detailed set of Turkish agricultural policy instruments such as direct payments, support prices, and import tariffs was developed.

The development of appropriate resilience strategies to address drought is typically based on the results of projections of future climate conditions, including those associated with extreme events. An important step in the planning process is to create a detailed set of procedures to ensure adequate plan evaluation. Periodic testing, evaluation, and updating of the drought plan are essential to keep the plan responsive to local, regional, or national needs and settings. To maximize the effectiveness of the system, the Turkish Agricultural Drought Action Plan is being implemented in Turkey.

5.4.3.6 Australia

Australia has the highest levels of naturally occurring, year-to-year rainfall variability in the world [75]. Yet, drought in Australia had long been regarded by policymakers as an aberration to an otherwise long-term “normal” climate pattern [6,16]. Further, [15] and [16] pointedly noted that from the time of European settlement, Australian Governments “responded to the concept of drought being a natural disaster through various Commonwealth-State natural disaster relief arrangements which treated drought in a similar manner to disasters such as tropical cyclones or floods.”

Over the past 40 years, climate science has provided a major contribution to improved understanding of the reasons for this high level of climatic variability with advances in seasonal forecasting research providing incentives for primary producers to adopt a more self-reliant approach to their farming operations, including drought preparedness. Over 20 major scientific publications pointed to aspects of the key climatic mechanisms—mainly associated with the El Niño phenomenon—are now known to be responsible for drought events in Australia. Some of these publications also pointed to the means of forecasting such extreme climate events, which implied the potential to prepare for drought events. Coincident enhancement of farming technologies over this period further enabled producers to create more drought-resilient systems. Australian Governments have also provided many incentives to improve self-reliance and farm management and so assist preparedness for the drought seasons and years when they occur. Government policy development over this period has been conducted with an awareness of all these factors and has therefore been able to provide changes in drought assistance through new policy endeavors that are probably unequalled in the world.

5.4.3.6.1 Climate Variability Links to Production Variability

In a further understanding of the linkages between climate variability, climate mechanisms, and agricultural management systems in Australia, Meinke and Stone [76,100] provided a description of the main, and many, climate drivers that exist across temporal scales and that can be linked to drought occurrence and other extremes of climate variability in Australia. Importantly, they described the relationships that exist between these many climatic mechanisms and agricultural management practices, also operating at these scales. This type of approach demonstrated that clear relationships could then be established between an understanding of the many modes of climatic variability and the many modes of "real" farm and agricultural value chain decisions.

5.4.3.6.2 Coincident Evolution and Diversification of Australian Agriculture

In the face of high levels of year-to-year climatic variability in Australia, land use and farming systems have nevertheless evolved and diversified, especially in the past four decades, largely responding to commodity prices, market arrangements, and, importantly, variability in natural resource conditions (including climate).

Coincident technological advances have resulted in improved cereal grain yields in many Australian regions, notably where crops have been more diversified in regions of somewhat more reliable rainfall.

A major technological advancement that is further suggested, in addition to the improved understanding of key climatic mechanisms over this period in Australia, has been the realization of the key value of the use of crop simulation modeling to aid in planning for agricultural drought purposes. In particular, the Agricultural Production Systems Simulator (APSIM) [58] provides simulated historical and future yields of crops and pastures, incorporating climate information, especially seasonal climate forecasting information, as an integral component of the output. In this, APSIM assimilates key soil processes (water, nitrogen, and carbon) and surface residue dynamics and erosion to provide a range of management options that can involve selected crop rotations and fallowing options. A further associated technological advancement has been the capability to provide prerun APSIM outputs as a form of decision support DSSs to aid in the preparedness for extremes in climate variability, including likely low rainfall periods that can be coupled with very low antecedent soil moisture conditions. Such a DSS, known as "Whopper Cropper" [21], can provide support to such decisions as "when to sow my sorghum crop with an impending low rainfall period (and potential drought), given poor starting conditions."

5.4.3.6.3 Development of Risk Management Capabilities and Key Policy Initiatives

Importantly, the Australian Drought Policy Review Task Force Review team identified its focus as "The concept of risk management is central to the philosophy of this review"—and it set out its vision of the role of both government and farmers in achieving a sound drought response. It argued that any government assistance should

- Be provided in an adjustment context
- Be based on a loans-only policy
- Permit the income support needs of rural households to be addressed in more extreme situations

5.4.3.6.4 Removal of Drought from Natural Disaster Relief Arrangements

Thus, a critical and fundamental shift in Australian drought policy occurred with the removal of drought from the natural disaster relief arrangements with the view then developed from increasingly convincing sources (as noted earlier) that drought and high levels of variability in agricultural production in Australia were actually a "normal part of a farmer's operating environment" and should be managed like any other business risk. However, an additional important step was that an accompanying package of programs was put in place to support farmers as they improved their risk management skills. This policy also introduced the concept of "exceptional circumstances" to cover events of such severity that they would be considered beyond the scope of good risk management [121,126]. In this respect, it has been noted that meanwhile, in the United States, individual states were the policy innovators for drought management [123], in contrast to Australia, where the federal government has provided most of the leadership, in concert with the states, for the development of a national drought policy [121].

Therefore, in parallel with core that is focused on agricultural research and development activities emanating from notable research institutions, there have been valuable developments in Australian state and territory government policies and programs that have sought to assist Australian farm businesses to manage their risks, especially the coincident financial risks such as the following:

- Farm Management Deposits, which have assisted farmers to better manage the financial variability that can arise from climate variability and market fluctuations.
- Tax relief measures—farm income averaging and fuel rebates.
- A suite of DSSs and tools, many with links to seasonal climate forecasting, include the notable Bureau of Meteorology web-based services and outputs (e.g., "Water and the Land"), state-based and state industry-focused outputs such as "the Long Paddock" (Queensland) monthly seasonal updates, and industry-specific services.
- Training and farm business planning, for example, "Plan, Prepare, and Prosper" workshops for farm planning management.

5.4.3.7 Americas

5.4.3.7.1 South America

5.4.3.7.1.1 Brazil Brazil has a variety of climates, ranging from tropical in the center north to temperate in the south and from humid at the north part of the Amazon region to semiarid at Sertão Region in greater part of northeastern Brazil. Such droughts are often related to the ENSO phenomenon. The positive ENSO phase, known as El Niño, is normally related to droughts in the northern part of the country, including the Amazon rainforest and the semiarid northeast, within which the State of Ceará is located. The negative ENSO phase (La Niña) normally intensifies the drought spells in southern Brazil.

The recent drought (2010–2013), but most impactful during (2012–2013) in the northeast, has been one of the worst in the past 100 years [18], especially during 2013, in terms of water availability, proving devastating to some agricultural, livestock, and industrial producers.

In Brazil, drought monitoring and early warning is supported by an array of various ministries and agencies, including the following:

- *Weather and climate forecasting*: National Institute for Amazonian Research; the Center for Weather Forecasting and Climate Studies (CPTEC), which belongs to the National Institute for Space Research (INPE); and the National Center of Monitoring and Early Warning on Natural Disasters. All of these entities are linked to the Ministry of Science, Technology and Innovation (MCTI). The National Institute of Meteorology (INMET) also performs weather and climate forecasting.
- *Water resources information*: ANA, within the MMA, captures water data from a hydrometeorologic network with 283 telemetric stations, 1075 fluviometric stations, and another 981 rainfall stations, all of which are distributed across the 12 Brazilian hydrographic regions. The information is captured and processed in Data Collecting Platforms, in partnership with the satellites of INPE. It aims at improving the evaluation of energy potential and the realization of water balance in "almost real time," in order to improve control of water resources, to make current data available to society, and to provide a broad conceptualization of rational and multiple water use. ANA also recently signed a cooperation agreement with many states that have state agencies sending their data to ANA.
- *Agrometeorological information*: INMET and Agrometeorological Information System (AGRITEMPO) of EMBRAPA (Brazilian Agricultural Research Company) are linked to the Ministry of Agriculture, Livestock and Supply (MAPA). By 2014, in partnership with the Interamerican Institute of Cooperation for Agriculture (IICA) and the WMO, INMET expected to have innovative and consolidated technologies in the areas of weather forecasting, meteorological observations, storage and processing of data, modeling, simulation scenarios, climatology, remote sensing, monitoring, research, and development fully deployed. This will promote the integration with national and international meteorological systems and propel greater ownership of INMET products by conventional users and farmers. This effort presents an opportunity for also improving drought preparedness through better coordinated monitoring and early warning/forecasting.

- *Research*: Laboratories and federal universities are of great importance for national drought monitoring. Still, many of the most innovative efforts in this realm are at state level, such as the following: Foundation Cearense for Meteorology and Water Resources; Centre for Meteorological and Climate Research Applied to Agriculture; Institute of Astronomy, Geophysics and Atmospheric Sciences; Institute of Meteorological Research; Technological Institute of Paraná, Centre for Information on Environmental Resources and Hydrometeorology of Santa Catarina, and University Center of Study and Research on Disasters in Santa Catarina (CEPED/UFSC), among others.

Despite the work of several federal and state agencies to develop monitoring/forecasting and early warning systems, the precision, coordination, and use of these systems need further improvement in order to allow for more efficient and informed decision-making. The atmospheric and oceanic field collection stations as well as the models made possible by the data collection station are regarded as models made possible by the data collection station that is regarded as relatively of high quality.

Finally, there have been proposals over the past few years to institutionally integrate efforts, through an Agreement of Cooperation between INMET (essentially the equipment and data collection infrastructure) and CPTEC (essentially the technicians and tools developers). The ultimate purpose would be to build a monitoring system, integrating products (tablets, mobile, and web) and applications, in collaboration with CENAD. Again, along with the INMET/IICA technological innovation initiative, bringing INMET and CPTEC together for the purpose of better institutional coordination represents an important opportunity to improve drought preparedness through monitoring and early warning. In this context, it would also be important to include ANA/MMA to ensure that hydrological data and information are also integrated.

5.4.3.7.2 North America

5.4.3.7.2.1 Mexico Traditionally, drought effects in Mexico have been attended through governmental reactive efforts directed to provide water and food, to assure health protection, and to restore economic impact once the phenomena are underway. The National Drought Program, PRONACOSE, by its Spanish acronym has its main focus on reducing vulnerability through the implementation of planned preventive actions under a comprehensive and participative approach.

Mexico's National Drought Program for the period 2013–2018 has a comprehensive and participative approach in several ways:

- *It includes both* prevention and mitigation through, respectively, the estimation of needed resources, the definition of actions, and the construction of a structure for the organization of stakeholders and the reduction of impacts on people, goods, infrastructure, activities, as well as on the environment.
- *It enhances* forecasting, early warning, and data dissemination, which includes both (1) the periodic collection and analysis of hydrometric and climatic data and information of reservoirs and that of drought location or its levels or degrees of intensity and (2) the spreading of drought information to guide the implementation of actions.
- *It promotes* coordination of governments from the federal, state, and municipal levels (for joint programs and resources) and water users involvement. The latter includes training for understanding the monitoring information and the options for user cooperation in water demand reduction actions and an efficient water use.
- *It supports* a drought plan for each of the 26 basin councils and drought plans for major water users. The first implies that authorities and users within their respective basin council design and later implement their plan based on local features. The plans for major water users look for specific actions for them (major water utilities, irrigation districts, or industrial facilities).
- The local implementation also implies that water users and authorities in the basin council will define triggers to implement agreed actions based on official drought evolution information. Also they should agree on a range of voluntary measures, which are expected to bring major water economies as well as mandatory measures.

A key principle is that the development of such plans implies increasing complexity and improvement with time (a dynamic planning), but it is expected that an increasing involvement of stakeholders will come with the time of implementation as well as with evaluation and feedback.

5.4.3.7.2.2 The United States Farmers implement a variety of strategies to manage weather and climate risks to agriculture. Such strategies include choosing suitable locations to farm, varying planting dates, diversifying crops and varieties, seeking alternative sources of income, maintaining an emergency fund, storing harvested crops on-site, and choosing sustainable farming techniques. The decision to apply one or more of these strategies is often in the hands of individual farmers. Thus, these strategies are most effective when farmers are well educated in basic risk management concepts and have access to the data and tools required to apply these principles. Significantly, this information not only empowers farmers to make sound risk management decisions but also enables them to retain management control of their agricultural activities throughout the process.

Another strategy that some farmers pursue is to transfer a portion of the risk to outside organizations. Contracting and insurance are two forms of external assistance that farmers often use to reduce their vulnerability to extreme weather and climate events. Production contracts can guarantee prices and markets for commodities, but such contracts often require farmers to follow prescribed production processes, thereby relinquishing at least some control of their farms to external entities. Crop yield insurance can help offset potential financial losses when yields fall short of insured levels, while crop production insurance can help offset potential losses when gross farm revenue is less than minimally acceptable. Insurance typically requires farmers to pay premiums, however, which thereby reduces potential farm profits. The availability and effectiveness of external assistance vary throughout the region.

Educating farmers on how to manage weather and climate risks to agriculture is an important step toward reducing their exposure to weather and climate extremes. This knowledge has little value, however, if farmers are not equipped with the data, tools, and applications necessary to apply risk management strategies on their farms. Locating and identifying these weather and climate resources can sometimes be difficult. The World Agrometeorological Information Service (http://www.wamis.org/) has helped address this issue by directing farmers toward these valuable sources of information [98,99]. Nevertheless, more work must be done to identify and raise the visibility of existing agrometeorological products and services and to improve farmer access to these resources. The National Meteorological and Hydrological Services, Ministries of Agriculture, and other groups can support this endeavor by more aggressively advertising available products and services and by streamlining farmer access to these data, tools, and applications.

5.4.4 Strategic Options

The strategic drought management options to be implanted in water-stressed/water-scarce regions are described in seven major strategic actions including

- Water harvesting
- Management of nonconventional resources
- Water conservation and saving in urban areas
- Water conservation and savings in landscape and recreational uses
- Water conservation in dryland agriculture
- Water savings and conservation in irrigated agriculture
- Social, economic, cultural, legal, and institutional constraints and issues

5.4.4.1 Water Harvesting

Water harvesting refers to methods used to collect water from sources where the water is widely dispersed and quickly changes location or form and becomes unavailable or that is occurring in quantities and at locations where it is unusable unless some intervention is practiced to gather the water to locations where it can provide benefits.

There are a number of water-harvesting techniques that are practiced in many of the water-scarce areas of the world. However, there are many other techniques that have developed from local necessity in sympathy with the local physical conditions and customs that could be adapted to benefit populations in other water-scarce locations. A large number of such practices have been described in a number of papers by Pereira et al. [86] and by Khouri et al. [62]. A number of the widely practiced techniques are discussed in the following text.

5.4.4.1.1 Rainwater Collection

Rainwater can provide a considerable water resource, not only in humid regions but also in semiarid and arid regions. Large volumes of water flow from roofs. In many regions, roof water has not been collected because traditional roofing materials did not permit easy collection and storage of collected water was difficult and expensive. However, in recent years, the availability of some forms of roof sheeting and innovative ideas for water storage has made roof water a serious resource. There is a great need to encourage its use and to teach simple, low-cost means of collecting water from roofs and constructing suitable storage facilities.

5.4.4.1.2 Small Dams

In regions of high evaporation, small and shallow dams are usually a cause of high evaporation losses. A major difficulty in the management of small water supply dams is siltation. Small dams will usually be constructed on small headwater streams. These are often steep and can carry large amounts of silt. If no attention is given to sediment control, most small headwater dams will fill with sediment within a few years, with almost total loss of the water source and the effort and/or capital invested in the construction. A common mechanism is use of sediment traps, which need to be constructed to allow easy maintenance. The sediment will need to be removed periodically.

The increase in freshwater storage capacity to meet growing demand has sparked considerable interest in methods for evaporation suppression. Following the pioneering work of Mansfield [72] on the use of chemical surface films, various types of surface covers for evaporation suppression ranging from monomolecular films, continuous plastic covers, suspended shading covers to modular floating elements have been proposed [5,17,73]. Interpretation of evaporation suppression efficiency from these studies was often empirical and qualitative and thus of limited value for quantitative comparative economic evaluation or for engineering design of various configurations.

Invariably, all large-scale methods provide only a partial cover of water surface, and solutions vary primarily by their maintenance needs, installation costs, performance, and lifetime. Typical modular floating elements used to suppress evaporation from reservoirs are shaped as polygons, squares, disks, or spheres [5]. Circular or spherical floating elements are available at a variety of sizes.

It is important to note that suspended covers were less efficient in suppressing evaporation than floating covers presumably due to formation of a vapor-saturated layer below the openings.

5.4.4.1.3 Methods of Artificial Recharge

The artificial groundwater recharge schemes may be classified under two broad groups:

1. The indirect methods through which increased recharge is achieved by locating the means of groundwater abstraction as close as possible to areas where surface water is in contact with the aquifer or areas of natural water discharge. In such cases, the natural hydraulic gradient is affected so as to cause increased recharge.
2. The direct methods through which surface water is conveyed from lakes, reservoirs, and wastewater treatment plants or is being diverted from flowing streams to suitable areas of aquifers where it is made to infiltrate to the groundwater from basins, trenches, dry riverbeds, injection wells, pits, etc.

5.4.4.2 Nonconventional Resources

Whenever good quality water is scarce, water of inferior quality will have to be considered for use in agriculture, irrigation of lawns and gardens, washing of pavements, and other uses not requiring high-quality water. Inferior quality water is also designated as nonconventional water or marginal quality water. Pescod [87] defined nonconventional water as water that possesses certain characteristics that have the potential to cause problems when it is used for an intended purpose. Thus, the use of nonconventional water requires adoption of more complex management practices and more stringent monitoring procedures than when good quality water is used.

Nonconventional waters most commonly include saline water, brackish water, agricultural drainage water, water containing toxic elements and sediments, as well as treated or untreated wastewater effluents. All these are waters of inferior or marginal quality. Also included under the designation of nonconventional waters are the desalinated water and water obtained by fog capturing.

The use of wastewater in agriculture is already expanding, particularly in water-scarce regions. Wastewater use will result in the conservation of higher-quality water and its use for purposes other than irrigation. The nitrogen and phosphorus content of sewage might reduce the requirements for commercial fertilizers. As the marginal cost of alternative supplies of good quality water will usually be higher in water-scarce areas, it is important to incorporate agricultural reuse into water resources and land use planning.

Desalinated waters are commonly added to the freshwaters for domestic uses. They are free from toxic substances or pathogens and can, therefore, be used to satisfy most human requirements. By contrast, because of its low level of salts and the high costs associated with treatment, desalinized water is less appropriate for agricultural uses.

Cloud seeding is a process of augmenting rainfall by adding substances to the cold clouds that act as nuclei for the formation of large water drops that otherwise would not fall to the ground. Its interest is however limited by the lack of cold wet air masses traveling over the arid low-lying areas where populations live.

Water importation mainly consists of transferring water from a basin where it may be in excess to the demand into another basin where water demand is much above the natural supply. Generally, this concerns long-distance water transfer from basins in subhumid to humid regions into semiarid areas. These transfers may be quite effective from a water management perspective, but they may create large environmental and developmental impacts in both the region from where the water is transferred and the region where it becomes available unless appropriate management and monitoring is applied.

5.4.4.3 Water Conservation and Water Saving in Urban Areas

The main supply problems faced in urban centers include the overexploitation and depletion of the water supply sources, their contamination, high costs of operation and maintenance of supply systems, increased competition with other water uses (agriculture, industry, recreation), observation of water quality standards, and avoidance of water wastes [14].

Cities often face a high incidence of leaks, the use of water-wasteful technologies, very low levels of water reuse, less appropriate water pricing and billing systems, water revenues that often do not cover costs, and a lack of public awareness of water scarcity. Unfortunately, these problems are more acute in water-scarce regions and less-developed countries than in temperate climates and developed countries.

Urban water supplies are used in households, industry, and commercial areas, as well as for urban services such as city washing, combating fire, maintenance of recreational lakes and swimming pools, and irrigation of recreational areas. Water conservation and water savings are required in all these domains, both in the hands of the users and directly by the municipal authorities.

Water conservation and water savings in an urban water system include water metering, leak detection and repair, water pricing and billing, service performance, use of water in municipal and public areas and services, and development of public awareness on water saving. These items are developed in the following, and the respective main issues, benefits, and limitations are summarized in Table 5.7.

TABLE 5.7 Water Conservation and Water Saving in Urban Areas

Issue	Benefits	Limitations	Effectiveness
System monitoring and metering	• Information on the system-state variables • Estimation of system water losses, locations, and causes • Base for planning water conservation measures • Support for implementation of water savings	• High investment and operational costs, mainly when an information system is created • Needs an information system to be fully effective	High to very high
Metering	• Provides fair billing • Allows water conservation planning • Induces adoption of water savings by customers	• Needs investment costs • May require system modernization in case of old systems	High to very high
Water pricing and billing	• Induces water savings when prices increase with used volumes • Helps people to appreciate the water supply, including giving water a social value	Requires well-designed price structure to be socially acceptable[a] and economically feasible[b]	High
Leak detection and repair	• Reduces volume of nonbeneficial water use • Reduces energy consumption, wear of equipment, and operational costs • Reduces contamination risks of the network • Induces positive water conservation behavior of customers • Allows more water availability to satisfy the demand	Requires implementation of appropriate technologies from a variety of technologies[c]	High
Maintenance	• Prevents equipment and conduit failures • Minimizes system water losses • Supports good service	• Requires system monitoring • Requires appropriate technical staff	High
Regulation and control devices	• Support appropriate hydraulic functioning of the network, including the avoidance of sudden variations in pressure due to the maneuver of gates and pumping stations in relation to variations in demand, which could damage conduits and equipment • Prevent system failures • Prevent the contamination of the network • Provide flexibility in operation • Maintain adequate service pressure, mainly when the network covers areas with less favorable topography, with large variations in elevation	• Require appropriate technical staff • High investment costs	High
High service performance	• Makes the customer responsive to water conservation policies • Gives confidence to the customer to adopt water saving practices	• Customer-oriented service requires high-quality operation and management • Higher costs	High
Separated distribution of high-quality and reused water	• Conserves good quality water to uses requiring such quality • Implies wastewater treatment • Allows effective water reuse for nonhuman and outdoor recreational uses	• Very high investment costs • Higher operation costs than for a single line distributor • Requires the involvement of the users	High to very high
Legislation and regulations	• Create a framework for adopting water conservation and saving • Enforce restriction policies when drought increases scarcity • Favor connections with public water authorities	• Need an appropriate institutional system for enforcement	High when enforced

(*Continued*)

TABLE 5.7 (*Continued*) Water Conservation and Water Saving in Urban Areas

Issue	Benefits	Limitations	Effectiveness
Economic incentives and penalties	• Favor the adoption of water saving devices and practices • Discourage water wastage	• Require appropriate institutional framework • Need careful planning[d]	High to very high
Public education and information	• Create public awareness of water conservation • Promote the adoption of water saving practices and devices by customers and the population	Require well-planned and coordinated efforts of public authorities, schools, water companies, and municipalities	High

[a] A number of key alternative mechanisms exist through which decisions can be made about who should be granted access to water. Often, these decisions are made by administrative authorities or according to communal water management rules. However, an important alternative approach is to allocate water on the basis of market mechanisms, particularly in the case of reallocation of water.

The introduction of water markets has been part of a shift in paradigm in water policy in many countries over the last two to three decades. This has seen a move away from "command-and-control" to more decentralized and market-driven policies. Full cost recovery, water markets, and the devolution of water management issues to local levels have been key components of this process. Globally, this process has been promoted by major international organizations such as the UN, the World Bank, and the OECD.

In addition to the introduction of an increasing range of water markets in formal national water policymaking, informal and local water markets are widespread. Indeed, there are few water management contexts globally in which no water trading of any kind takes place. In considering water markets, therefore, the appropriate question is not whether trading per se should take place but on what form of trading can facilitate the desired social and environmental objectives [49,83,133].

[b] Historically, in most countries, water costs have largely been or still are subsidized. In others, water is supplied free. It is of importance to establish rate policies that emphasize greater user involvement in water conservation and saving. When users are charged appropriately for water services, the water use as well as the water waste tends to decrease. Water pricing can help to save water if the price structure meets some essential conditions:

Prices must reflect the actual costs of supply and delivery to the customers to ensure the sustainability of the water supply services and the maintenance of conduits and equipment.

The price rate should increase when the water use also increases to induce customers to adopt water saving and conservation.

Different price rates should be practiced for diverse types of water use in municipal supply, for example, differentiating domestic indoor uses from gardening water uses; when water is more scarce than usual, prices for less essential uses could be modified earlier.

Differential increases in price must be large enough to encourage water savings.

Prices must reflect the quality of service, that is, poor and nonreliable service cannot be provided at high cost but costs must change as soon as service is improved.

Any change in pricing must be accompanied by information and education programs that support an increased awareness of the customers of the value of water and water supply services.

[c] Some of the strategic leak detection technologies include the following:

Acoustic method, based on the fact that leaks under pressure produce sounds that can be detected by using appropriate sensors, amplifiers, and headphones

Swiss method consisting of injecting water under pressure into a reach or a sector of the network and measuring the amount of water required to keep the pressure constant, where the resulting volume equals the amount of water leaked

Correlation analyzer method, which is based on recording the noise produced by a leak using sensors placed up- and downstream of it and then processing the two signals by a correlation analyzer to give the respective distances to the leak location

Tracing method, where tracers are injected upstream and then the leak site is detected with the support of chemical or radioactive tools [44].

[d] Incentives to urban customers are required when the implementation of water savings implies investments in homes and buildings, in particular for low-income populations. Examples are the installation of modified supply and sewerage systems when separate supply and sewerage networks become available in the neighborhood, the replacement of toilets for reduced flush volumes, or the adoption of pressure control devices. Incentives could then be given by the government, the municipality, or the water supply company. Incentives by the government to the water company and the customers generally relate to the following:

Credit facilities relative to a specific investment for water conservation and saving

Lowering or exempting custom taxes for selected goods or equipment

Subsidizing a percentage of the investment costs, which could vary with the income level of the customers

Fiscal benefits for the water company or the customers in relation to selected investments

5.4.4.4 Water Conservation and Savings in Landscape and Recreational Uses

Landscape and recreational water uses include a variety of outdoor and indoor uses and can be managed by municipal, governmental, or private institutions, but all have in common the fact they are for public use. Water conservation and water saving issues are summarized in Table 5.8.

5.4.4.5 Water Conservation in Dryland Agriculture

Dryland agriculture is traditionally practiced in water-scarce areas when rainfall during the rainy season is sufficient for the crop to develop and produce. Yields are commonly lower than for irrigated agriculture and vary in a large range from 1 year to the other, following the trends in the temporal variation of precipitation. The use of water conservation practices is usually required for successful crop production under water-scarce conditions. Water conservation in dryland agriculture may assume quite different facets and include the selection of crops that are less affected by rain water deficits, the adoption of cropping practices that favor the ability of crops to escape water stress, and soil management practices that help to conserve water in the soil for crop use. A recent review has been produced by Unger and Howell [105]. In semiarid and arid conditions and when drought occurs, the water deficit periods during the crop season may be quite large, and supplemental irrigation and water harvesting become part of dry farming practices. A summary of the mechanisms of crop resistance to water stress is presented in Table 5.9.

TABLE 5.8 Issues in Water Conservation and Saving in Recreational Water Uses

Water Use	Issues	Applicability
Gardens and lawns	• Selection of ornamental plants less sensitive to water stress • Adopt water reuse • Adopt well-designed and automated drip and microspray irrigation systems • Establish irrigation management strategies to cope with increased levels of water scarcity • Irrigate by night • Use soil mulch and weed control	Requires technological support and training of personnel to be effective
Pools and ponds	• Use water purification tools when not used to support life, such as fish • When having fish, use a technique similar to fish ponds, or flowing water for other uses, e.g., irrigation tanks	Requires planning and technical support to personnel
Golf courses	• Adopt an irrigation design oriented for easy management under scarcity • Reuse treated wastewater for irrigation • Establish irrigation management strategies to cope with increased levels of water scarcity	Requires new approaches in design and management and training of personnel
Parks and lakes	• Enforce water quality policies • Adopt integrated resource management	Needs involvement of public authorities
Sport areas	• Sprinkler irrigation of green areas with high uniformity • Adopt precise irrigation	Requires technical support
Swimming pools	• Use purification tools and chemicals • Enforce health prevention measures	Easy
Indoor facilities	• Adopt controlled flush toilets • Adopt limited flow showers • Use time controlled hand-wash taps • Use controlled discharge kitchen taps • Care for leak detection and repair	For most of the issues, they follow common sense practices.
General issues	• Publicize water saving measures • Advertise to make water users aware • Educate children and youth	Favors public behavior

TABLE 5.9 Drought Resistance Mechanisms, Traits, and Benefits for Crops to Cope with Water Scarcity

Mechanism	Traits	Benefits
Drought escape[a]		
Rapid phenological development	• Short biological cycle • Special morphological • characteristics	• Reduced seasonal crop water requirements • Lower reduction in seed numbers
Drought avoidance		
Reduction of water losses		
• High stomatal resistance • Reduced evaporative • surface • Low radiation interception • High leaf cuticle resistance	• Size, number, and opening of stomata • Leaf rolling, smaller and fewer leaves, senescence • Leaf pubescence and leaf orientation • Thicker and tighter leaf cuticles and waxiness	• Reduced transpiration • Reduced transpiration and less radiation absorbed • Higher reflectivity and less radiation absorbed • Lower transpiration and lesser desiccation effects
More efficient water extraction from the soil		
• Larger root depth and density • Larger liquid-phase conductance	• More extensive and intensive rooting • More or larger xylem in roots and stems	• Lower resistance for water uptake by the roots • Lower resistance to water fluxes from roots to leaves
Drought tolerance[b]		
• Ability to maintain turgor of cells • Tissue water capacitance • Desiccation tolerance • Accumulation of solutes	• Water potential kinetics and cell characteristics • Favorable water potential kinetics • Protoplasmic and chloroplast conditions • Abscisic acid, ethylene, and others	• Decrease osmotic potential in response to stress • Ability to maintain the daily water balance • Maintaining photosynthetic activity • Regulation of leaf senescence and abscission

[a] *Drought escape* refers to plant's physiological characteristics typical of arid environments that make plants escape from prolonged periods of water stress, as is the case for plants that develop very fast and have a quite short biological cycle, or that have morphological characteristics that favor reduced impacts of insufficient water availability.

[b] *Drought avoidance* consists of plant characteristics that result to reduced transpiration and improved conditions to extract water from the soil.

Given the severity of drought in dry areas, a central challenge for researchers is to devise technologies that lend greater resilience to agricultural production under this stress. One way in which they have responded successfully to the challenge is by developing varieties of major food crops that are drought tolerant or escape drought through early maturity.

To speed the progress of breeding for drought tolerance, scientists are actively employing two sets of cutting-edge tools. One is derived from molecular biology and involves the use of molecular markers to better understand the genetic basis of drought tolerance and to select more efficiently for this trait. The other, called participatory plant breeding, offers a more active role to farmers, who are keen observers of plant performance and can contribute importantly to selection for better drought tolerance [23].

5.4.4.6 Water Savings and Conservation in Irrigated Agriculture

5.4.4.6.1 Demand Management

Demand management for irrigation, in the context of coping with water scarcity, consists of reducing crop irrigation requirements, adopting irrigation practices that lead to higher irrigation performances and water saving, controlling system water losses, and increasing yields and income per unit of water used. It includes practices and management decisions of an agronomic, economic, and technical nature.

The objectives of irrigation demand management can be summarized as follows:

- *Reduced water demand* through selection of low demand crop varieties or crop patterns and adopting deficit irrigation, that is, deliberately allowing crop stress due to under irrigation, which is essentially an agronomic and economic decision.
- *Water saving/conservation,* mainly by improving the irrigation systems, particularly the uniformity of water distribution and the application efficiency, reuse of water spills and runoff return flows, controlling evaporation from soil, and adopting soil management practices appropriate for augmenting the soil water reserve, which are technical considerations.
- *Higher yields per unit of water,* which requires adopting best farming practices, that is, practices well adapted to the prevailing environmental conditions, and avoiding crop stress at critical periods. These improvements result from a combination of agronomic and irrigation practices.
- *Higher farmer income,* which implies to farm for high-quality products and to select cash crops. This improvement is related mainly to economic decisions.

Improvements in surface irrigation systems that help cope with water scarcity are numerous and depend upon actual field conditions. They relate to improvements in water advance conditions, increased uniformity of water distribution in the entire field, easy control of the water depths applied, and reducing deep percolation and runoff return flows. These improvements are briefly referred to in Table 5.10, where expected benefits and common limitations for implementation are also included.

5.4.4.6.2 Supply Management

The importance of supply management strategies to cope with water scarcity is well identified in the literature and observed in practice, particularly for surface irrigation systems, which constitute the majority of large and medium water systems in water-scarce regions.

Supply management is generally considered under the perspective of enhancing reservoir and conveyance capabilities to provide higher reliability and flexibility of deliveries required for improved demand management. This is true not only for irrigation systems as mentioned earlier but also for nonagricultural water uses. Therefore, supply management includes the following:

- *Increased storage capacities*, including large reservoirs with capacities for interannual regulation and small reservoirs, namely, for supplemental irrigation
- *Improved conveyance and distribution systems*, including compensation and intermediate reservoirs for improving the flexibility of deliveries and avoiding system water losses during periods of low

TABLE 5.10 Improvements in Surface Irrigation Systems Aimed at Reducing Volumes Applied and Increasing the Water Productivity to Cope with Water Scarcity

Techniques	Benefits	Applicability
Land leveling (precision leveling)	Less water to complete advance, better conditions for adopting deficit irrigation and control of the leaching fraction	Requires support to small farmers
Irrigation with anticipated cut-off	Reduced water application; runoff is avoided and percolation is minimal.	Easy to apply when available water is limited
Basin irrigation		
Higher discharges, reduced widths, and/or shorter lengths	Fast advance time, reduced volumes applied, easier application of deficit irrigation, and control of the leaching fraction	Easy; limitations are due to field size and geometry.
Higher basin dikes to catch storm rainfall	Provide full conjunctive use of irrigation and rainfall	Easy to implement, mainly for paddy fields
Corrugated basin irrigation for row crops	Faster advance, improved emergence and rooting of the crops planted on the bed, easy introduction of row crops in rotation with rice	Easy to implement
Maintaining low water depths in rice basins	Lower seepage and percolation losses and better conditions to store any storm rainfall	Limitations when land leveling is poor and delivery is infrequent
Nonflooded paddies, i.e., maintaining the soil water near saturation	Lower seepage, deep percolation and evaporation losses, and better conditions to store any storm rainfall	Only for paddies in warm climates and when deliveries are frequent
Furrows and borders		
Irrigation with alternate furrows	Reduced water application to the entire field and deep rooting of the crops are favored.	Easy to apply
Reuse of tail water runoff	Avoidance of runoff losses, increased system efficiency, and control of quality of return flows	Need for collective facilities in small farms
Closed furrows and borders	Avoiding runoff at the downstream end	Easy (in flat lands)
Contour furrows	Runoff and erosion control in sloping land	When fields are not oriented downslope
Surge flow	Faster advance, reduced percolation and runoff losses and higher performance and provides for system automation	Easy for large farms but difficult for small ones
Continuously decreased inflow rates (cablegation)	Control of percolation and runoff losses by continuously adjusting flow rates to infiltration and provides system automation	Requires technological support and is difficult for small farmers
Improved furrow bed forms	Improved furrow hydraulics and infiltration that favor other improvements for water saving	Requires appropriate implements, large farms
On-farm water distribution		
Gated pipes and layflat pipes	Easier control of discharges, control of seepage, provides automation	Easy to adopt but require farmers' investment
Buried pipes for basins and borders	Easier control of discharges and seepage and easy to be automated	Less appropriate for small farms
Lined on-farm distribution canals	Easier control of discharges when siphons and gates are used and control of seepage losses	Only for large farms
Good construction of on-farm earth canals	Easier control of discharges when using siphons and some control of seepage losses	Limitations due to farm implements available
Automation and remote control of farm systems	Improved conditions for operation, easier application of improved irrigation scheduling, including in real time, and precise irrigation management techniques	Application only to large farms with high technological and financial capabilities

TABLE 5.11 Supply Management for Water Conservation in Agriculture

Objective	Technology
Increased storage	Small reservoirs for runoff storage groundwater recharge from excess runoff
Increase water yield	Water harvesting vegetation management to control runoff
Increased use of rainfall	Spate irrigation microcatchments, land forming terracing conservation tillage
Add to available supplies	Unconventional water system reservoirs, conveyance, and intrabasin transfers

demand, as well as improved regulation and control, including automation and remote control, to favor that deliveries match the demand
- *Good maintenance* of reservoir and conveyance systems, which is a precondition for water saving and the reliability of deliveries
- Development of *new sources of water supplies* to cope with extreme conditions of water scarcity, as it is the case for droughts

Supply management is also considered under the perspective of system operation, particularly related to delivery scheduling, thus including the following:

- *Hydrometeorological networks*, databases, and information systems to produce appropriate information for effective implementation and exploration of real-time operation of irrigation systems
- *Agrometeorological irrigation information systems* including tools for farmers to access to information, often comprising GIS, and to support local or regional irrigation management programs as well as DSSs serving the reservoir operation, the water system management, and the users to select crop patterns, irrigation scheduling, and irrigation systems
- *Planning for droughts* to establish allocation and delivery policies and drought operation rules

Supply management for irrigation also refers to the farm water conservation, as indicated in Table 5.11.

The management of irrigation and multipurpose water supply systems to cope with water scarcity includes the utilization of a variety of managerial techniques and tools that are summarized in Table 5.12. Particular references are made to irrigation systems because these systems are the most frequent and larger water systems in water-scarce regions. However, outlined issues also apply to municipal and industrial uses with due adaptations to the respective operational conditions since these systems are generally pressurized, have centralized control, and operate regularly throughout the year.

5.4.4.7 Social, Economic, Cultural, Legal, and Institutional Constraints and Issues

5.4.4.7.1 Water Conservation Education

In most urban areas, it is common to see large quantities of water being wasted due to thoughtlessness or carelessness. Many urban dwellers take their water supply for granted and have little appreciation of its value. Almost all urban dwellers worldwide need continual reminders of the importance of saving water. This is particularly true in water-scarce areas. As discussed in the next chapter, there is a need to continually provide education to all urban dwellers, beginning with small children, concerning the need to conserve our precious water resources. People need to be shown that small changes in behavior, such as properly closing taps and minimizing water for bathing, can reduce consumption by up to 50%.

5.4.4.7.2 Educating Children and Youths

Education of small children on water issues must be a long-term strategy and therefore once begun must continue—forever. The benefits of educating the young ones on water issues can be that for the rest of their lives, these people will be aware of water issues and are likely to be open to consider new thinking on how water can be used more effectively, less wastefully, and with less environmental impacts.

TABLE 5.12 Management of Irrigation and Multipurpose Supply Systems to Cope with Water Scarcity

Management Techniques	Benefits	Applicability
Add to supply for drought mitigation		
New sources of surface water, short-distance water transfers	Increase local water availability	Difficult, needs integrated planning
Increased groundwater pumping	Adds to normal water sources	Needs control/monitoring
Transfer of water rights	Reallocation of available water	In accordance with existing water laws
Use/reuse of low-quality water for irrigation and landscape	Alternative sources of water	Depending on crops and uses, monitoring required
Conjunctive use	Maximizes the use of available rainfall and water resource	Needs appropriate planning and management
Reinforce the use of other nonconventional waters	Prevents extreme scarcity	Where nonconventional waters are already in use
Improved reservoir operation		
Information systems, including remote sensing, GIS, models	Information for optimized operation and management	Nonlimited but expensive for small schemes
Hydrological forecasting and drought watch systems	Improved assessment of supplies	At large scale, large projects or regional level
Upgrading monitoring	Improved use of operation tools	General but involving costs
Application of optimization, risk, and decision models	Optimized management rules and water allocation	Nonlimited but expensive for small schemes
Conveyance and distribution systems		
Canal lining	Avoidance of seepage losses	Limited by costs
Improved regulation and control	Higher flexibility, better service, and reduced operation losses	Needs investment and technology
Automation and remote control in canal management	Improved delivery management and low operation losses	High technological requirements
Low-pressure pipe distributors	Reduced spills and leaks, higher flexibility, easier water metering	Limited by costs but easy to implement
Change from supply-oriented to demand-oriented delivery schedules	Favors farmers to apply water saving irrigation management	Needs communication tools
Intermediate storage (in canal, reservoirs, farm ponds)	Increased flexibility and reduced operation losses	Requires investment and management tools

(*Continued*)

TABLE 5.12 (*Continued*) Management of Irrigation and Multipurpose Supply Systems to Cope with Water Scarcity

Management Techniques	Benefits	Applicability
Involve farmers in delivery schedules planning to cope with limited supply	Allows farmers to adopt best management practices	Needs appropriate institutional arrangements
Adopt demand delivery scheduling in pressurized systems	Higher flexibility for water savings at farm	Only constrained by the system characteristics
Water prices in relation to volumes of water diverted and times for use	Induce farmers to save water and to irrigate by night (automation)	Requires appropriate water metering and water pricing
Information systems	Provides for optimized operation maintenance and management	General but primarily to large schemes
Application of optimization methods to schedule deliveries	Increased reliability and equity and reduced farm demand	Needs feedback information from farmers
Maintenance and management		
Effective system maintenance	Avoids spills and leaks and improves operation conditions	Requires planning and trained staff
Water metering	Data for operation and billing	Requires equipment
Monitoring system functioning	Identification of critical areas and system losses	Requires planning and staff
Assessment of system performances (physical, environmental, service)	Provides follow-up on water saving programs	As above
Personnel training	Allows to implement more demanding technologies	General, not highly costly when well planned
Information to farmers and other users	Knowledge on the system constraints and saving issues	General

5.4.4.7.2.1 Schools

All school curricula should include instruction on water issues appropriate to the region and to the age of the children. In regions with water scarcity, the instruction should deal with minimization of water use and protection of water from contamination. Instruction should begin at the school entry level and should continue through all years of school attendance. At secondary school level, syllabi could consider innovative ideas on water collection, water treatment, wastewater treatment, and water reuse. The need for the implementation of some of these ideas will be obvious to children in water-scarce regions, and the contributions they can make to developing new ideas for conserving water should be fostered and welcomed by their communities.

5.4.4.7.3 The Role of Women

In many regions, particularly those where water is scarce, the role of women is very important:

- Women have a large influence in shaping the attitudes of the young ones, the future majority of the population.
- Women often have a large role (with children) in water collection, where there is no direct household supply.
- Women largely control in-house water use.

5.4.4.7.4 Farmers and Industrial Water Users

Here, there are usually very large opportunities to save water. University courses on irrigation and industrial water use put large emphasis on optimal water use. Unfortunately, much less effort is made to transfer these ideas to the individuals who are directly involved in using the water, and these individuals are unlikely to have had any opportunity to participate in university courses. As a result, in many water-scarce regions, the farmers and industrial water users consume very large quantities of water for quite small productivity. Some of the responsibility for the resulting waste lies with inefficient water laws, water allocation arrangements, and water pricing structures [134].

There need to be large incentives to encourage farmers to make optimal use of water. Incentives should be made available to farmers adopting water saving and conservation tools, such as for investments relative to purchase the equipments for improving the irrigation systems or to adopt conservation tillage. Similarly, financial incentives are appropriate when farmers adopt deficit irrigation or adopt water reuse schemes or make good use of treated wastewater.

Even incentives by themselves are not sufficient. Programs of education for farmers are needed. These need to be run by well-trained extension workers who have time to work with the farmers to show them how to make better use of their water. Alongside this dispatch of extension advisers to the farms, there need to be well-publicized, easily accessible demonstration farms where optimal water use is practiced and where farmers can see for themselves the potential benefits of good water use practices.

Farmers will respond quickly when they see with their own eyes that the returns they could reap for their labor could be increased many times, especially, as will usually be the case, where the physical effort and time required may be no more than for their current practices. Educational programs for farmers should be well linked with farmer extension programs, including demonstration.

Similar incentives are needed for industrial water users. Incentives can be in the form of subsidies for purchase of more water use–efficient plant, encouragement of water reuse by removing taxes from recycling plants, by increasing the price of input raw water, or combinations of these. The need is to maximize returns per unit of water, to minimize the unproductive loss of community water, and to minimize environmental damage.

5.4.4.7.5 Research

Research is needed on how to effectively communicate water saving ideas to farmers, industrial operators, and households. In every culture, some different approaches will be needed. The aim should be to discover how to raise the consciousness of everyone in the community to the reality that water is scarce and very precious. Everyone in the community needs to be encouraged not just to stop wasting water but to look for ideas on how to get more value from every drop of water.

5.5 Summary and Conclusions

The practices and managerial tools have been outlined as a guide for further selecting, evaluating, and then implementing those more adequate to a given region or country: It has been documented that adoption of water management strategies not only is a technological problem but also involves many other considerations relative to the social behavior of the urban and rural communities, the economic constraints, or the legal and institutional framework that may favor the adoption of some measures and not others. Moreover, adopting water management practices and tools requires that a better knowledge of the water scarcity regimes be developed; water be given a social, economic, and environmental value in agreement with the society; and education for water be effectively implemented through a structured process among all stakeholders.

Difficulties on predicting droughts are well known: Nevertheless, an adequate lead time—the period between the release of the prediction and the actual onset of the predicted hazard—is more important than the accuracy of the prediction. It is the lead time that makes it possible for decision and policymakers to implement policies and measures to mitigate the effects of drought.

In recent years, concern has grown worldwide that droughts may be increasing in frequency and severity given the changing climatic conditions: Responses and associated management strategies to droughts in most parts of the world are generally reactive in terms of crisis management and are known to be untimely and poorly coordinated. Nations need to move from reactive, crisis management mode to proactive programs based on national drought policies, including the following:

- Effective monitoring and early warning systems to deliver timely information to decision-makers
- Effective impact assessment procedures
- Proactive risk management measures
- Preparedness plans aimed at increasing the coping capacity
- Effective emergency response programs directed at reducing the impacts of drought

It is also essential for countries in drought-prone areas to develop management plans and strategies for dealing with drought and for addressing the emergency needs resulting from such an occurrence. Management plans should be defined and prepared for implementation with wide participation so as to better prepare the whole country/region for the next drought occurrence.

In general terms, the usual objectives for drought management in water-scarce regions are almost always in conflict with each other and so compromises are usually required: The conflicts are increased by the numerous different subobjectives of the individual water users and land holders. Conflicts will always occur because there are many users, with diverse interests and aims, all needing to obtain their supply from a single, limited (scarce) source. There is a large potential for inequities of supply and for those with power to dominate and take a large share of the limited resource. Similarly, inequities and less-than-optimal water use tend to be encouraged by inflexible political, institutional, or management systems. As with most technologies, efficient water resources use and management schemes can change rapidly and rigid institutional arrangements can often stand in the way of the changes that may be needed to develop or encourage the "best" methods of allocating water to the many potential users. As such, water scarcity should encourage lateral thinking and flexibility in approaching water supply needs.

The building blocks of effective and sustainable drought management strategies include the following:

- *Participation*: All citizens should have a voice—directly or through intermediate organizations—representing their interests in policy and decision-making. Broad participation hinges on national and local governments following an inclusive approach.

- *Transparency*: Information should flow freely within a society; processes and decisions should be transparent and open for public scrutiny. Right to access this information should be clearly stated.
- *Equity*: All groups in the society should have equal opportunities to improve their well-being.
- *Accountability*: Governments, the private sector, and civil society organizations should all be accountable to the public.
- *Coherence*: Because of the increasing complexity of water issues, policies and actions must be coherent, consistent, and easily understood.
- *Responsiveness*: Institutions and processes should serve all stakeholders and respond properly to preferences, changes in demand, or other new circumstances.
- *Integration*: Water governance should enhance and promote integrated and holistic approaches.
- *Ethics*: Water governance must be based on the ethical principles of the society where it functions—for example, by respecting traditional water rights.

The plans have to be followed by examples of action to account for different environmental and socioeconomic realities:

- Every drought has unique problems and impacts; therefore, it is difficult to present a plan that details and addresses all of them.
- The social and economic structure of every basin or water unit is different, and examples are used to show the range of possible application of the guidelines.
- There is already valuable information and knowledge of drought management in agricultural and water supply systems, and the examples enhance the exchange of experiences.
- The guidelines are not prescriptive; they simply offer a range of options based on real case studies.

Research is a critical aspect that allows stakeholders integrate their strategic actions confidently and with sustainable social acceptance.

The science of optimal water use is not yet perfect, and there are many areas where there are opportunities for making more efficient use of limited water resources. Irrigation offers many opportunities to use less water to obtain the same crop production. Evaporation reduction is always a challenge. Not only is research needed for these fundamental issues, but there are also many opportunities to save water in local situations by encouraging small changes in current practices. Research is needed both to discover where savings are possible and to find ways to encourage changing of some traditional or even culturally based practices.

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6

Drought Management in an Urban Context

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Abstract Drought is usually a regional phenomenon, which, at times, can have wider consequences. It is a feature of natural cycles on the planet. It can affect all living and most nonliving systems on Earth. When the concentration/density of such populations is great, the impact of drought can be more, given the limited resources—water in its many forms—are shared by a large number of users. Cities, including all scales of urbanization where human populations are larger than at other habited centers, are prime examples of densely populated areas where effects of drought can be exacerbated by limited resources, due to increased user groups in a smaller geographical area.

6.1 Introduction

Of the world's entire water content, only a very small fraction, a mere 2.5%, is freshwater. Of this limited freshwater available, 87.3% is trapped in polar ice caps and glaciers, 12.3% is in underground reservoirs, and only 0.4% is available on the surface or in the atmosphere in a form suitable for direct consumption by humans, animals, and plant life as well as for industrial or agricultural use [29]. Thus, less than 0.01% of all water is readily available for land-based life. Major demands for this limited resource by people are in agriculture followed by industry. Domestic water usage is only a very small part of overall water demand, with many parts of the world suffering chronic shortage [9,15]. Drought affects many human endeavors, especially food production through agriculture and animal husbandry.

The history of mankind strongly suggests that urbanization has been part of human evolution. Earliest settlements, with agriculture as the main industry, created cities where a large number of people, including farmers and other associated professions, lived. Archaeological research has unearthed many evidences for this. In some cases, the reasons for their decline have been attributed to long-term climatic changes, most of them drought related. When drought persists in a region, agriculture declines and people have to move on to other areas with more water availability. This could be considered one reason for prehistoric migrations of people that established human footprint to the extent that we see today.

This chapter investigates the relationship between urbanization and management of drought and water scarcity in an urban context. The term "urban" could be subjective given the different sizes in which cities appear around the world, between poorer countries and more affluent ones.

6.2 Drought and Human Habitation

6.2.1 Water for Human Use

Water is one of the most important resources used by humans and all other living organisms. Our food revolution and industrial development depend on it, more importantly our day-to-day existence depends on the availability of clean and safe water. The availability of water for safe use and management of hygiene and sanitation has been at the forefront of human settlement from earliest civilizations. Human endeavor and innovation has always been driven by this single resource more than any other. Among the ancient wonders, the mythical Hanging Gardens of Babylon is said to have sourced water from far-away rivers through an ingenious and intricate tunnel system to combat local water scarcity.

6.2.2 Urban Scene

The major cities have been ranked based on their population by UN. Tokyo has more city dwellers than any other place on Earth with 38 million people, while Delhi, Shanghai, Mexico City, Sao Paulo, and Mumbai closely follow in population size. Together, the world's cities contain more than half of the total human population, at 54%. It is expected to reach 66% by 2050. A majority of projected urban growth will occur in Asia and Africa, with more developing or underdeveloped countries.

Data presented by World Bank [39] show an upward trend in urban population change in most countries with a similar trend presented for urban areas of a population more than 1 million. This is in contrast to a stable number of residents in the largest city of a country as a percentage of urban population within the country. Together, this could mean that more regions in the country would have attained the status of "city." It is projected that by 2030 we will have 41 megacities with more than 10 million people [38], an increase from 28 megacities in 2014 (Figure 6.1).

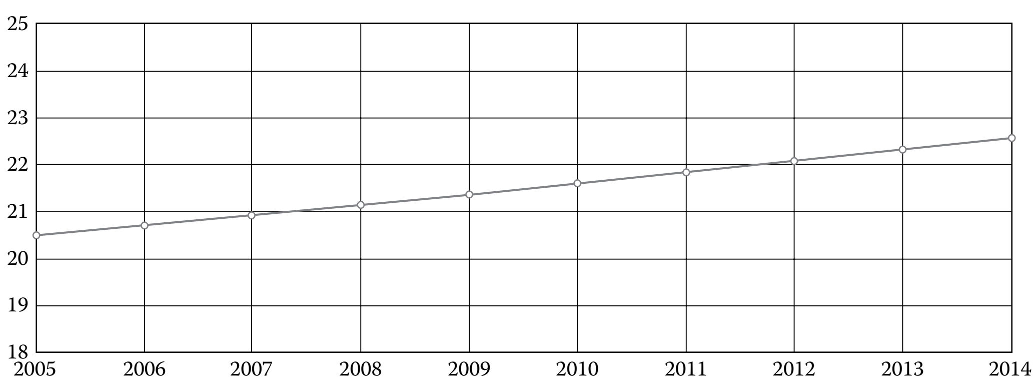

FIGURE 6.1 World urban population growth. (From World Bank, Online data bank, 2015, accessed on September 15, 2015, data.worldbank.org.)

The urban environment is characterized by less natural vegetation and more heat-retaining man-made structures. Increased occurrence of vehicular transportation adds considerable amount of greenhouse gases to the atmosphere, contributing to anthropogenic climate change and global warming. Regional global warming felt in urban areas, compared to rural regions with more natural vegetation, farmlands, and other heat sinks, can be exacerbated in hotter climate, drought, and generally in summer.

6.2.3 Drought and Urbanization in History

Urbanization has evolved with changes in human endeavors and environmental conditions. Preindustrial notions of urbanization could be considered primitive in comparison with contemporary scales of postindustrialization. Ancient civilizations and their cities around the world, many of which have now become defunct, performed well during those days, in part, due to conservative lifestyles and ways in which natural resources (arguably more abundant than now due to lower consumption rates) were considered and consumed. Effects of natural water cycles, including drought, have had immense impacts on their survival and existence, as evidenced by recent studies on historical centers of human habitation. Urbanization and food production were two social factors linked by human settlement in various parts of the preindustrial world. Food production, whether from intense agriculture, pastoralization of land for livestock management, or aqua farming for protein (including exploitation of marine and riverine resources), demanded constant availability of, and proximity to, water resources.

Impacts of environmental changes, including drought and desertification around the world, have been the subject of various studies reported in the literature. Dillehay et al. [12] studied ancient civilizations in Peru, their water usage patterns and abandonment of land at various periods by analyzing soil profiles and employing carbon dating techniques. The stratigraphic profile of agricultural land, irrigation canal system, and other practices shed light into an era spanning several hundreds of years and touch upon the climatic variability impacting upon the availability of water for human use. Their study revealed intermittent desertification and catastrophic flooding occurred in ancient Peru, disrupting human habitation in the urban settlements.

Chronic drought is more disadvantageous to intense agriculture, an unavoidable feature of urbanization, than short-term events such as flooding. Drought conditions demand innovation in sustainable practices such as changes in agricultural patterns including shift from intense forms of agriculture and livestock management to more small-scale activities. Impact of flooding is more evident, usually, than that of drought. Nevertheless, effects of water on the rise, fall, and adaptation (including relocation) of ancient urban civilizations are evident in soil profiles.

In assessing historical changes in urbanization around the world related to weather events, a certain level of cognizance could be achieved that can be valuable in modeling for the future. However, this is affected by data availability and inaccuracies. Domínguez-Castro et al. [13] studied climate considerations as noted in the Islamic chronicles in the urbanized Iberian Peninsula during AD 711–1492. The research focused on documented events relating to extreme droughts, and it is noted that periods of drought always coincided with periods of famine (e.g., AD 873–874 and AD 898) in the region that, at times, led to extreme measures taken by the population, including cannibalism.

Schimmelmann et al. [34] compared various extreme weather events across a 2000-year period in a geological area spanning from California through Mesoamerica to South America. This is an area that has experienced severe droughts in recent times as well. The study suggested an approximate time frame of 200 years where paleo-climatic changes were spaced and also identified a matching pattern with cultural changes among local civilizations at such time periods. It has been suggested that weather events such as droughts, through reduced agricultural productivity (and presumably other effects as well, including water for other consumptive uses) indirectly cause social disruption and cultural decline in populated regions such as urban areas.

Notwithstanding the human-induced fast-paced climate change of present times, climate change has always occurred in the past. Bernhardt [6] studied the effects of climate variability on the evolution of human settlements in the Florida Everglades region in the past 4000 years. The Everglades cover an area of ~6000 km^2 and is a phosphorus-limited, precipitation-driven, subtropical wetland system. The tree islands of the Everglades have been found to have evolved during drought periods in its long history and the local Native American populations evolved along with them, adapting their fishing and hunting activities. This could be one of the earliest urban adaptations to drought conditions in the history of mankind.

6.3 Management of Drought, Anywhere

The environmental impacts of drought can be felt in a wider geographical area than the immediate area it is experienced in. This is due to side effects such as desertification, reduction of soil moisture affecting crop and natural vegetation, increased surface reflectivity of solar rays, falling groundwater tables, pollution, and emigration by communities. The perception of the four types of drought—meteorological (climatological), agricultural, hydrological, and socioeconomic—can be varied across different sections of communities based on several factors, including the economic status, back up options for water availability, extent of drought, predictability of return to normal conditions, etc.

The key to understanding drought is to grasp its natural and social dimensions, with the management of drought focusing on the affected community's coping capacity, resilience, and practical management of drought assistance. Preparing to address future droughts requires a risk-based approach in analyzing and adapting to potential and prevalent conditions. Drought impact monitoring is required to identify interactions between natural characteristics of meteorological drought and human activities that depend on precipitation to meet societal and environmental demands, as well as to determine appropriate management responses to drought. Extensive drought can lead to desertification, which can encroach into urban centers located on the fringes of such areas [30].

Effective management of the risks to water resources and food security via drought adaptation and sustainable farming practices requires reliable monitoring and prediction of drought and precipitation. Several agencies provide drought monitoring and prediction services around the world. The Global Water Partnership's Integrated Drought Management Framework, the U.S. Drought Monitor, and the Experimental African Drought Monitor are some international examples. Most of these services employ different assessment techniques and various indices in providing early warning.

Australia is one of the countries that experiences the widest rainfall variability and thus natural climate variability [20,22]. Much of eastern Australia, where the more populated cities are located, has been drought declared for a long time. Intensified by climate change, the hydrological cycle and extreme weather events can exacerbate the risk of drought and water scarcity in the world's driest inhabited continent. Recent years have seen severe drought and severe floods in many parts of the country. In larger geographical regions such as Australia, there may not be a direct link between rainfall and drought. This situation arises, for example, in the dry tropical region of northern Australia (less urban) when rainfall deficiencies over several months or even years may have only limited impact on the availability of water resources, which is quite different from eastern Australia (more urban). Therefore, the integration of rainfall information with appropriate agricultural and hydrological models is critical in improving our understanding of drought impacts.

Australian governments shifted their view of drought from "natural disaster" to a "manageable risk" in 1990 following a review of natural disaster relief arrangements [19]. This had immense impacts on national policy development. The viewpoint, it can be argued, slightly shifted from an environmental issue to take on a social issue façade. Higgins [19] touched upon the assumption that risk characteristics would be uniform across a particular society. This is not always correct as the risk, for example, that of drought, may affect individual members of a society differently. People whose professions are closer to nature, such as farmers, could have different direct effects than others. In view of forming national policies, subgroups of the national populace, such as rural and urban, will be impacted differently.

Globally, agriculture is a major user of freshwater, and drought affects availability and management of water. Smart technologies have been developed to integrate several services and parameters such as drought monitoring and prediction, water storage, need and availability, usage patterns, and the like. Lessons from historical data and possibilities of impending onslaughts of drought based on changing weather patterns and climate regimes necessitate water-proofing the food bowl based on where water is available. This would require considerable policy development and infrastructure spending with the latter focusing on water storage and conveyancing where innovative construction methods should be applied.

Forward planning should involve better efficiency in the utilization of the deployed infrastructure. This also needs uptake of smart connectivity, modern telemetry, and real-time reporting for water quality and quantity monitoring—when and where water is needed. Infrastructure requirements for commercial viability of drought management in irrigated agricultural and livestock projects to benefit the economy would include water storage, pipelines, and associated infrastructure and smart water distribution network.

Hughes [20] undertook a comparison of wastewater recycling in the United States (focusing on California) and Australia. Both California and Australia experience severe drought conditions, high urban populations and income levels. It should also be noted that most domestic wastewater is produced by urban areas, making this an urban water resourcing issue. Treated wastewater is usually used in replacing, in part, reliance on fresh water resources for domestic/industrial use. However, even when faced with severe drought conditions, members of the public can prove to offer localized resistances against reuse of treated wastewater due to preconceived notions based on ill-informed decisions. Effective public education and policy formulation by institutionalized government authority structures are of paramount importance in dealing with such problems.

6.4 Management of Urban Drought

Management of drought in an urban environment is somewhat different to that in a rural area, especially with heavier population densities, less open spaces, and limited natural water bodies. The level of industrialization or economy can have an upper hand in the way such efforts can be directed toward future-proofing cities against drought. For example, a city on the coastal fringe may have advantages of proximity to a desalination plant as a source of potable water or as an "insurance policy" to assist in prolonged dry periods.

Many major cities harbor urban slums as "cities within cities," populated by people emigrating in search of jobs and better economic status. These are more prevalent in heavily populated developing countries. For many of them, the major concerns are spread of diseases, pollution due to lack of appropriate sewerage, or ocean encroachment due to sea-level rise in a changing climate, while inland cities experience issues that stem from drought and desertification instead of sea-level rise, which would threaten the informal settlements where economic development does not necessarily reach. Slums are characterized by overcrowding, poor quality housing, lack of basic infrastructure, poverty [35], and no access to educational and healthcare facilities. Water scarce conditions would make life harder in such situations.

Austin [3] analyzed data on 135 nations for a triple bottom line analysis on the movements and their health issues especially regarding tuberculosis (TB) and malaria, leading causes of death in such areas. It is noted that these diseases are still prevalent in poorer countries, especially in the arid Sub-Saharan, Southeast Asian, and Pacific regions. Lack of clean drinking water and disease vector spread by ponding of contaminated stagnant water contribute to this. One recommendation from this study was that national policies should be framed to include social issues characterized by slum conditions and the apparently vast socioeconomic and environmental differences from neighboring affluent urban areas in the same city.

Owing to the geographical differences culminating in entirely different issues, urban areas could be analyzed differentiating whether they are major coastal, major inland, or smaller cities irrespective of their economic affluence.

6.4.1 Coastal Cities

Considering most global cities are located in coastal areas, the effect of drought on coastal areas is of importance to global urban population. The impacts are not just on water for direct human consumption, it affects the sustainability of industrialization that provides employment to citizens and the overall livability of the cities in terms of maintenance of natural habitat. Many studies have been undertaken to study the effects of drought on various coastal endemic plants and trees [5,14,15].

The effects of drought on water cycle are much more emphasized in coastal areas due to naturally evolved soil conditions. Sheahan et al. [36] discussed these effects in terms of anthropogenic changes in microbial and chemical conveyancing systems and the dilution rate of surface water flow in drought conditions. Stagnant water bodies can harbor increased prevalence of disease vectors such as mosquitoes. Reduced surface flow can concentrate chemical pollutants. This, in turn, can cause bioaccumulation of chemicals and human pathogens in shellfish and other lower-order aquatic organisms, which can be exacerbated with increased salinity in drought conditions. On the other hand, a change in weather with increased precipitation can cause release of such concentrated pool of compounds, causing acute chemical pollution.

Monitoring of coastal drought can be undertaken via the measurement of vegetation water content as equivalent water thickness with remote sensing, measurement of surface water heat flux, and surface covering (by vegetation) as per Gao et al. [16]. This is useful in the management of nature parks in and surrounding urban areas created as heat sinks and nature retreats and national parks established within urban regions.

The most notable and researched coastal urban drought is that of cities in California on the pacific coast in the United States. Urban coastal drought in heavily populated cities such as San Francisco and Los Angeles has enormous implications for the local populations ranging from water restrictions and living standards to impacts on industrialization.

Arnold and Martin [2] studied historic drought on the Channel Islands of California and suggested that seasonal fluctuations in climatic patterns and its impacts on biodiversity are interlinked with human behavior factors. Carbon dating of plant remains revealed changes in biota and other evidence suggested importing of food from mainland during early periods (AD 1150–1300). The "Little Ice Age" of AD 1400–1850 had effects on most urban/semi-urban areas around the planet, including extended periods of drought [8]. This provides some insight into climate change in the preindustrial era.

Ortegren et al. [27] reported on summer drought variability at subregional level in southeastern United States, an area not usually associated with drought. The year 2007 was noted to be the driest on record in the region with more than $5B on economic losses predominantly in the farming sector. The authors analyzed climatic variability in terms of specific indices, details of which could be found elsewhere in this handbook. It is interesting to note that this same area is fraught with severe wet weather patterns including tornadoes (perhaps whereby a reduced interest is notable among research community on the warm weather drought effects in the area).

Australia is the most arid/dry inhabited continent on the planet, with a predominantly coastal settlement. Its major mainland cities have all experienced severe drought in recent years along with other severe effects of climate change. With a small population thinly spread across vast areas, Australia has been able to manage water scarcity better than many other countries, with management options including desalination plants, time-of-day and day-of-week based water restrictions, environmental flows management, etc.

The hunter valley in New South Wales (NSW), Australia, is mildly urbanized with a high proportion of farming and mining activities with interspersed towns and one medium city. Higginbotham et al. [18] conducted a survey among 1162 residents on perceptions on climate risk including drought. The results revealed that the community's biggest concern was regarding drought, heat, plant death along with changes in established norms of seasons and weather patterns. People in the lower regions had concerns about other effects of climate change as well, such as sea-level rise and property value decline. It is noted that the climate concerns have affected people's behavior toward valuing nature more, conserving water, reducing energy use, etc.

On the other hand, the poorer countries in Africa have experienced chronic drought in varying levels throughout the continent, affecting the overall lifestyles and livelihood of communities. Coastal areas in Egypt experience less than 150 mm annual rainfall with a recent long spell of drought from 1995 to 2011.

The area under study by Aboul-Naga et al. [1] had experienced rapid urbanization with predominantly sustenance herders with a mix of goats, sheep, and camel. Measures taken by the community to adapt to the chronic water shortages included a reduction in the size of the herd or an increase in the percentage of goats in the flock, as goats require less water or can adapt themselves to relying only on natural vegetation without the need for dedicated pasture lands.

6.4.2 Inland Cities

Human settlements have always been concentrated based on the availability of water for various needs such as agricultural, industrial, commercial, and municipal. Many cities around the world are located away from coastal regions either on river banks (e.g., Moscow), lake sides (e.g., Chicago) or at the confluence of many rivers (e.g., Delhi), ensuring access to water. In the case of major inland cities with high levels of urbanization, it can be seen that drought can have far-reaching consequences as it is not easy to bring water to inland cities.

Inland cities, due to lower humidity levels, could behave differently to coastal cities in the presentation of drought effects on populations. Li [24] suggested that large inland cities such as Beijing might see more tolerable urban heat island effects in dry conditions. Other inland urbanized areas such as Chongqing may have other issues in a severe drought as two-thirds of the population are engaged in agriculture. In this instance, the term "city/urban area" means differently as the number of people alone would not define an urban area. Whether urban or semi-urban, population increase and inland migrations to cities would increase water demand, which will be a governance, social, environmental, and public health issue in times of drought.

6.4.3 Smaller Cities or Towns

Other than major cities as mentioned in the preceding paragraphs, many smaller cities and towns were established on the banks of streams and other forms of surface water. It could be seen that a risk of running out of water has been accepted or ignored, knowingly or unknowingly. The UN [38] reported that nearly half of the world's urban population resides in smaller cities or towns with many of such regions growing at an alarming rate.

Bruggen et al. [7] and Patz [31] reviewed effects of drought on water supply in urbanized areas within developing countries. High population growth and lack of adequate financing of water infrastructure were noted to affect cities and towns in developing countries. It has been noted that, lack of priority can cause similar frustrations for lower social status areas even without a large population. A lack of access to water resources can pose an issue for old towns situated inland, which were mainly founded for other natural resources, such as old mining towns.

Effects of climate change are being predicted to affect developing countries in more ways than developed nations. Apart from inundation of coastal cities anywhere due to sea-level rise, an increase in drought conditions will affect policy development, which could see competition for the limited available resource. A case study by Tjandraatmadja et al. [37], assessing water security and impacts of climate change on Makassar city in Indonesia, pointed out that effects of climate change should be a priority in decision-making and policy development, in planning for infrastructure development and investment. Having successfully implemented infrastructure development plans in the larger cities does not necessarily mean that all the city dwellers would be benefited from it. Developing and implementing suitable (not one-fits-all) long-term governance plans for everyone including the marginalized communities is important, especially in areas that are ravaged by drought, flood, and other issues in succession [23,28,33].

This issue is worsened in areas suffering from long-term social unrest resulting in the absence of a local government for decision-making and policy implementation [25]. In such situations, even the global organizations that undertake rescue/peace-keeping missions have to prioritize resettlement and management of potential refugee crisis while long-term environmental aspects could get lower priority.

Without external influence by global agencies and NGOs, the situation could spiral into deeper calamities, which would render a return to normalcy harder to achieve. The development and implantation at grass roots level of sustainable drought management strategies would require long-term planning and action, contrary to short-term solutions possible with external involvement. For certain natural calamities such as earthquake and floods, such measures are more helpful than drought, which has a long-term footprint.

Drought monitoring generally can inform broader policy development for water management and is an important planning instrument; therefore, investment in drought monitoring and prediction services also becomes an important aspect for smaller towns and inland cities that would be more directly involved with farming activities. This brings food security for the wider population, including urban and otherwise, into the picture as an important planning and policy aspect. In this context, it can be argued that drought in an urban context is strongly related to urban in the rural context as societies in urban and rural settings are strongly interrelated via food web. A decline in food safety can be linked to poverty and decline in environmental conditions. It is interesting to note that the year 2006 was declared by the UN General Assembly as the International Year of Deserts and Desertification, an effect of chronic extreme drought, while the decade 1996–2006 was named the International Decade for the Eradication of Poverty by UN.

Rural poverty can be more severe and far reaching for sufferers than urban poverty; the impact of natural calamities, especially for people who rely on weather conditions to make a living, has greater risks. Hayati et al. [17] reported on the effects of drought in the Middle East on poverty and farmers in Iran, a water-scarce country with mean annual precipitation of only 250 mm. Drought causes failure of crop leading to food shortages, causes severe socioeconomic problems and psychological stress for the farmers, and affects local economy as a whole in the long term. Poor farmers in Iran were meted out with only nonspecific support by authorities that proved to be unhelpful.

Kasi [21] gave a deep insight into various external factors affecting the sustainable livelihoods of members of marginalized communities. One reported definition of sustainable livelihood is "the way in which people satisfy their needs, or gain a living" presumably in line with the ways of nature or with careful exploitation of locally available resources. This is especially relevant in assessing the effects of urban drought on urban poverty, such as in the outer suburbs, slums, and heavily populated cities of the developing world. The paper discussed a collaborative program between the Central Government of India and the State Government of Andhra Pradesh, focused on drought proofing the state, which includes the second-most arid place in the country. Though predominantly focusing on marginalized communities in semi-rural regions of the state, the high population density of the area makes the division, between semi-rural and semi-urban, thin—in one sense due to the varying definitions of the term "urbanization" as practically used in developed and developing country situations. Such programs, such as watershed development, are based on identifying water conservation and water harvesting opportunities—in other words, water-sensitive design with drought proofing as the theme.

6.4.4 Drought-Sensitive Urban Design

A careful integration of the design of our built environment with prevalent and futuristic water cycle management, or water-sensitive urban design (WSUD), has been the mantra for policy development in many developed countries for the management of fresh water and wastewater in the urban context. WSUD can be defined as the "integration of urban planning with the management, protection and conservation of the urban water cycle that ensures urban water management is sensitive to natural hydrological and ecological processes" [26].

In other words, it is urban development that uses, conserves, and enhances water resources in such a way that water cycle is maintained and total quality of life, present and future, is improved. In other words, it is urban design with a water conservation focus. In the face of extreme weather events leading to drought, this could take the form of drought-sensitive urban design as well, given lack of water is one theme of WSUD. Environmental flows need to be maintained to avoid river death and resulting ecological degradation downstream from dams and other water-retaining structures made to assist anthropocentric consumption. One of the main features of urban stormwater management is that of fast removal. The extensive pipe systems put in place in urban landscape design are aimed at quickly removing the stormwater away to avoid flooding. However, this also takes away any sporadic rainfall during extended drought periods.

Despite assurances from establishing backup plans for a drought period such as desalination plants that have high operating costs, lower rainfall and increased evaporation will have more impacts than lower runoff, creating "water sensitive cities" requiring innovative approaches to water capture, treatment, and water reuse incorporated in an integrated water management strategy. Coupled with early warning systems, drought monitoring and prediction services and proactive measures by the community as a whole, urban area can be prepared to be drought sensitive. This would mean WSUD becomes complementary to a "drought-sensitive urban design (DSUD)" approach.

A practical and operational model is required to incorporate into designing a water-sensitive community. An urban drought-prevention model is a handy tool in incorporating various parameters, including future climate change into today's design aspects. However, it does not offer a "one-size-fits-all" solution as precipitation, water stress, and climate variability differ vastly across different regions of the world, in countries such as the United Kingdom and Taiwan with ample rainfall being different to countries such as South Africa and Australia with limited rainfall.

Cheng et al. [10] developed a system that incorporated sustainable water management principles, limited natural resources and intended uses, employing statistical analyses and incorporation of a water reservoir into building design under a raft foundation, which is reportedly a typical local design feature. The study focused on a 12-storey building that incorporated this design feature. As per their design, the water in the dam served flush toilets and was replenished from local rainfall and supported water demand during urban drought periods.

Coutts et al. [11] reviewed urban heat effect in Australian cities in light of WSUD principles. Proper planning and incorporation of stormwater harvesting as part of WSUD can assist in retaining some of the rainfall in order to alleviate climate-dependent urban heating, especially in persistent hot summers and extended drought periods. This could be via assisting urban greening, soil moisture replenishment, feeding urban water features, etc. Beyond comfort, this has added advantages in dealing with health effects of acute urban heating such as heatstroke, dehydration, and heat syncope. This is important given Australia's aging population, summer lifestyles, and lack of atmospheric humidity.

Designing of urban features, including commercial and residential complexes in the cities, should also include smart air conditioning along with modern environmental sustainable design practices such as tri-generation, rainwater harvesting, various methods of solar energy capture, and green/live walls. This would assist with reducing adverse impacts of drought-induced urban heat effects. However, the proper upkeep of these features would be required in the long run so that the live walls remain alive and well. If required, precinct-level policy generation should be undertaken that assist building managers to implement them with assigned priority. As Hughes [20] suggested, local government authorities (such as city authorities) will be more in line with local requirements and local context, thereby reducing costs of implementation assistance and improving efficiency.

Predictability of drought, through modeling based on available local and global weather data, also feeds into decision-making. Prolonged drought periods culminating in extended water shortage experiences play a role in shaping urban water management policies and strategies.

6.5 Sustainability and Urban Drought Management in a Future World

Drought management requires a good level of predictability. A study by Panikkar et al. [30] indicated that a majority of users of weather data would prefer to have long-term monitoring and predictability to enable better decision-making for future proofing their operations against drought. The conventional focus of meteorological services to present information in the form of spatial weather maps may contribute to a continued focus on spatial technologies such as Geographical Information Systems (GIS) to present drought information, while not adequately developing improved capacity to present temporal information. The focus on spatial information is likely to grow as spatial technologies, remote sensing, and modeling capabilities continue to develop. But a balance is required to ensure that improvements in spatial technology do not constrain the development of improved predictive methods for temporal forecasts.

The environment of our future world, as suggested and warned by scientists around the world, faces severe and unpredictable weather events due to climate change induced by global warming caused by accelerated release of greenhouse gases from human activities. Despite efforts from naysayers trying to play down the facts evidenced by rigorous scientific research and forecasts, a growing body of undeniable proof indicates that unless careful and thoughtful proactive steps are taken, the effects of climate change will be problematic to the way of life that humans and other inhabitants of the planet Earth have known in recent times. Climate change is expected to reduce night-time cooling, due to reduced natural surfaces that are replaced with impervious surfaces thus increasing the urban heat island effects [11]. The obvious countereffort would be to increase vegetation in urban areas incorporating WSUD and other sustainable development measures.

The fast-paced economic growth and urban population increase has necessitated carefully planned adaptation to environmental changes especially in the Asia-Pacific region. Urban centers are more vulnerable to health and lifestyle impacts of climate change, compared to nonurban areas that have less population and more natural land offering resilience. This would mean that the more urbanized a country is, the more innovative it needs to be.

Australia is one of the most highly urbanized (with 89% urbanized population) and arid countries in the world with a wide range of thermal variations across seasons. Despite the high per capita income reported, there are poor communities especially among the Aborigines and other socioeconomically disadvantaged groups. Bambrick et al. [4] identified the strong need to work with community and other stakeholders, beyond the scientific understanding of climate change and its impacts, to develop and implement mitigation strategies to cope with future climate change–related weather impacts. This could include the incorporation of climate-sensitive urban design (CSUD) principles into residential construction, town planning, and building services. However, as Li [24] opined, a general lack of awareness and interest (beyond the immediate) in climate change adaptation by the wider public reduces stakeholder participation in policy discussions.

A UN-backed publication analyzing climate change and cities referred to the complex interconnected impacts of climate change on urban environment [32]. In the first report of the Urban Climate Change Research Network, the authors provided practical guidance on climate change adaptation and mitigation measures in the urban context. It has been noted that some cities, owing to human behavioral differences among other factors, will experience more urban heat island effects than others. This would mean that, during drought periods, such cities could experience severe impacts than other cities and surrounding land irrespective of the direct perceptions by communities. For countries with heavier reliance on hydropower, effects on cities would be exacerbated with lower water levels in the dams.

6.6 Summary and Conclusions

Drought, as a natural calamity, can affect any part of the world, without distinction of whether it is a developed or developing country, coastal or inland city, megacity or smaller town, or rural village. However, as a long-term event, how the affected communities can prepare for it and adapt to it is important. In urbanized areas, where the majority of human populations live, it is especially important as a mix of rich and poor cohabit in a small space devoid of much of its natural vegetation.

Greening of cities could ameliorate the urban heat effects from extended hot periods that accompany drought, with alternate plans to deliver water such as desalination plants and water recycling all of which involve a good deal of capital expenditure. In poor countries, financial constraints may impose restrictions, which could be overcome by international aid and volunteer work coordinated by global organizations such as UN, WaterAid, and Engineers Without Borders. Water-sensitive urban design is a practice that should be incorporated into town planning and development approvals with focus on potential drought and water scarcity conditions.

Several studies mentioned in this chapter, and several others available in literatures, will shed light into issues faced by developing countries, smaller cities, and towns even in rich countries as well as marginalized communities living in megacities (such as in slums). Proper, thoughtful, and long-term planned governance to distribute benefits of plans to manage drought is of utmost importance. Civil unrest could result not only from political issues but water-stress issues as well that should be managed appropriately where local governance is lacking or inadequate. Long-term predictability of drought has improved in recent times with added focus on climate change and its effects on natural calamities including drought and its evil cousin, floods, and how it affects urban areas. Rising sea levels and desertification are the two effects of climate change that could threaten urbanized populations, ironically, together, and mitigation measures need to be planned and implemented with several decades in view for the planning process. Additionally, the public themselves need to be resilient and undertake water-conserving measures, beyond merely for compliance with statutory requirements.

Author

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7

Drought Management in Coastal Areas

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Abstract A large proportion of the world's population (about 70%) dwells in coastal zones, many of which are so heavily urbanized that their need of freshwater for domestic, agricultural, and industrial supply is acute and increasing, whereas available water resources are scanty.

In many parts of the world, where alternative water resources are missing, the lack of good coastal water resources management schemes, as well as mismanagement, has led to groundwater overexploitation. Thus, groundwater resources tend to be insufficient to meet increasing water demand.

7.1 Introduction

Coastal areas are particularly vulnerable to droughts as the lack of precipitation causes a drastic freshwater outflow in rivers and aquifer systems, and in the long run, it upsets the fragile equilibrium between surface water and groundwater of different salinity. Therefore, surface water and groundwater are jeopardized by the combined effects of saltwater intrusion and pollution, with strong impacts on the emerged and submerged coastal ecosystem.

The growing water demand, due to rapid population growth and socioeconomic development, can be hardly satisfied with local resources, which mainly consist of groundwater sources and which might be insufficient to supply water of good quality for drinking, domestic, agricultural, irrigation, and industrial purposes.

Conflicts may arise among different users, especially when there is a seasonal peak demand for irrigation and drinking purposes, in addition to matching tourist sector needs.

Conventional and nonconventional water resources should be assessed and managed in an integrated way, considering quantity and quality demands for different purposes and local hydrogeological and economic characteristics.

7.2 Coastal Area and Aquifer System Definition

Coastal areas represent the final part of the hydrogeological catchments, where the fragile interface equilibrium between fresh, brackish, and saltwater is generally jeopardized by (1) natural processes such as sea-level variations, due to climate cycles, subsidence, floods, and tsunamis and (2) human actions such as freshwater overexploitation, drainage, and land reclamation. Under such situations, reduced aquifer recharge due to drought produces saltwater intrusion.

The *hydrogeological catchment* consists of an area of land where waters from rain and melting snow or ice converge as surface water and groundwater runoff to a single point at a lower elevation, usually the exit of the basin, where surface water and groundwater join another water body, which in coastal zones may be a wetland, like a pond, a lagoon, a salt marsh, or the sea (Figure 7.1).

The groundwater *recharge area* is a part of a hydrogeological catchment where effective precipitation and surface water are absorbed into the ground and then percolate into an *aquifer* (underground reservoir).

In a typical coastal aquifer system, a mass of groundwater flows toward the sea in (1) *unconfined aquifers* extended in depth from the open to the atmosphere through the permeable material, down to an underlying impervious bed, and (2) *confined aquifers*, bounded between impervious formations. The upper water surface (water table) of unconfined aquifers is at atmospheric pressure, and thus is able to rise and fall, depending on water recharge and drawdown. Water-table aquifers are usually closer to the Earth's surface than confined aquifers are, and as such are impacted by drought conditions sooner than confined aquifers.

In unconfined aquifers, the *water table* or *piezometric surface* is below the land surface. As a result, the effective pores are saturated only below it. In confined aquifers, effective pores are fully saturated as the water level in a well is higher than the bottom of the impervious top boundary layer. Effective pores are saturated below the water table, in the *saturation zone*, and unsaturated above it, in the *unsaturated zone*, where they are partly occupied by air, in various percentages depending on local infiltration mechanisms. Piezometric surfaces in unconfined and confined aquifers fluctuate in time with a certain lag depending

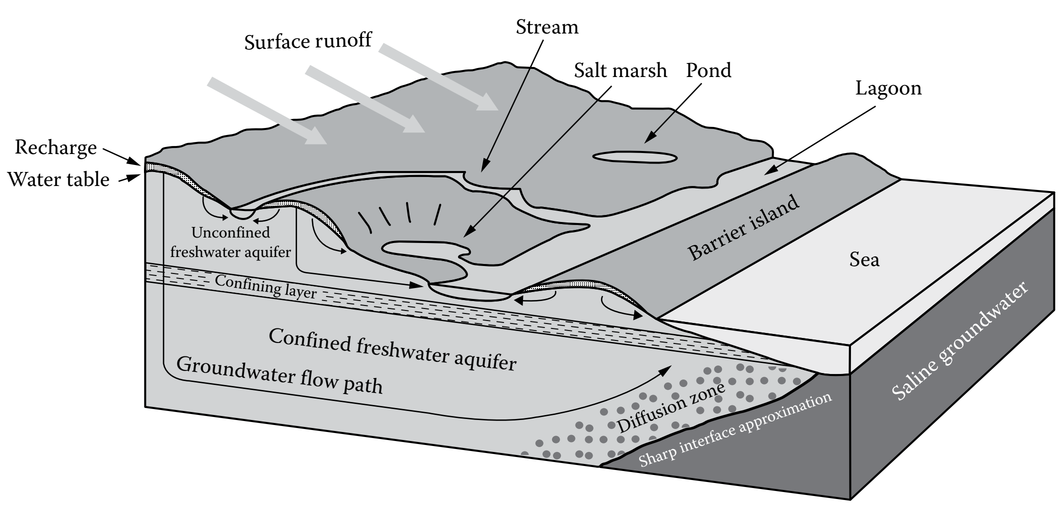

FIGURE 7.1 Schematic coastal aquifer system.

on the precipitation in the recharge area and the flow path from the recharge to the discharge area through the unsaturated and saturated zones.

Aquifer systems in coastal plains mainly consist of *porous media* formations, in beds of alluvial sediments from coarse to fine, interlayered between impervious clays beds and lenses. Owing to sea-level variations in time, the structure of major deltaic plains may be rather complex, and fossil freshwater and saltwater aquifer layers are often interbedded in depth below sea level [7]. Recent alluvial deposits normally overlay an ancient morphology bedrock, with valleys formed by rivers outflowing into the sea with a level much deeper than now (>100 m). Exploited groundwater is generally stored in the alluvial deposits of recent hydrographies.

Aquifers in *fractured media* are formed by crystalline, volcanic, and sedimentary nonkarstic rock bodies with secondary porosity due to ruptural deformations. Groundwater is stored and flows along fractures and joints of different systems, which should be defined according to their type. Tension fractures and overthrusts are much more conductive than shears, provided deposits from saturated waters have not naturally cemented them or filled them up with tight materials [6].

Karst is produced by solution due to rainwater flowing on the surface and percolated in depth along major fractures of soluble rocks such as limestones, dolomitic limestones, and gypsum. Rock joints and cracks are gradually widened and also deepened by hydromechanical erosion until they become cave systems or underground stream channels into which narrow vertical shafts may open. Karst process develops only in the unsaturated zone, above the water table. Submarine paleokarst phenomena clearly proof sea level variations in time, due to climate changes or structural earth crust deformations. Geometrical and hydraulic parameters in karstic media are higher than in fractured media. Where the aquifer is overexploited, under hydrodynamic conditions paleokarst may be reactivated and affect present-day groundwater flow. Karst is to be dated, as even paleokarst development may strongly affect present-day groundwater circulation and composition.

7.2.1 Recharge and Discharge Areas in National and Transboundary Hydrogeological Catchments

As stated by the Barcelona Convention on the Mediterranean Coastal Environment Protection (adopted on 16.12.76 and amended on 10.06.95) [89], "the hydrogeological basin may not coincide with the river basin collecting surface waters when groundwater recharge areas are partly or totally in bordering catchments, outside of the geomorphological water divide" (Figure 7.2).

The definitions of *transboundary aquifers* and *transboundary groundwater* describe groundwater that traverses international political boundaries, and *international aquifers* refer to groundwater bodies somehow extended across international political boundaries, like a purely domestic aquifer hydraulically linked to a transboundary river [30].

Hydrogeological basins may be crossed by national and regional borders, making the resource common to different countries and administrations. Furthermore, some considerable water volumes stored in large deep aquifers, as in North Africa, are nonrenewable resources, and their use is consequently not sustainable. These facts may cause conflicts between different regional and local water authorities.

7.2.2 Freshwater–Saltwater Interface and Groundwater Balance

Coastal regions represent *aquifer discharge areas* of fresh groundwater naturally or artificially recharged and generally floating on saltwater in variable proportions, depending on (1) the density difference between the two types of waters, (2) tides, and (3) well drawdown. The delay time, representing the time needed for the water infiltrated in the recharge area to reach the discharge area following varying hydraulic gradients, may range from many years for coastal plains and large peninsulas to days for small islands and nearshore recharge.

Badon Ghijben [4] and Herzberg [53] independently assumed that in a homogeneous unconfined coastal aquifer under hydrostatic conditions, the weight of a unit column of fresh water of density ρ_f

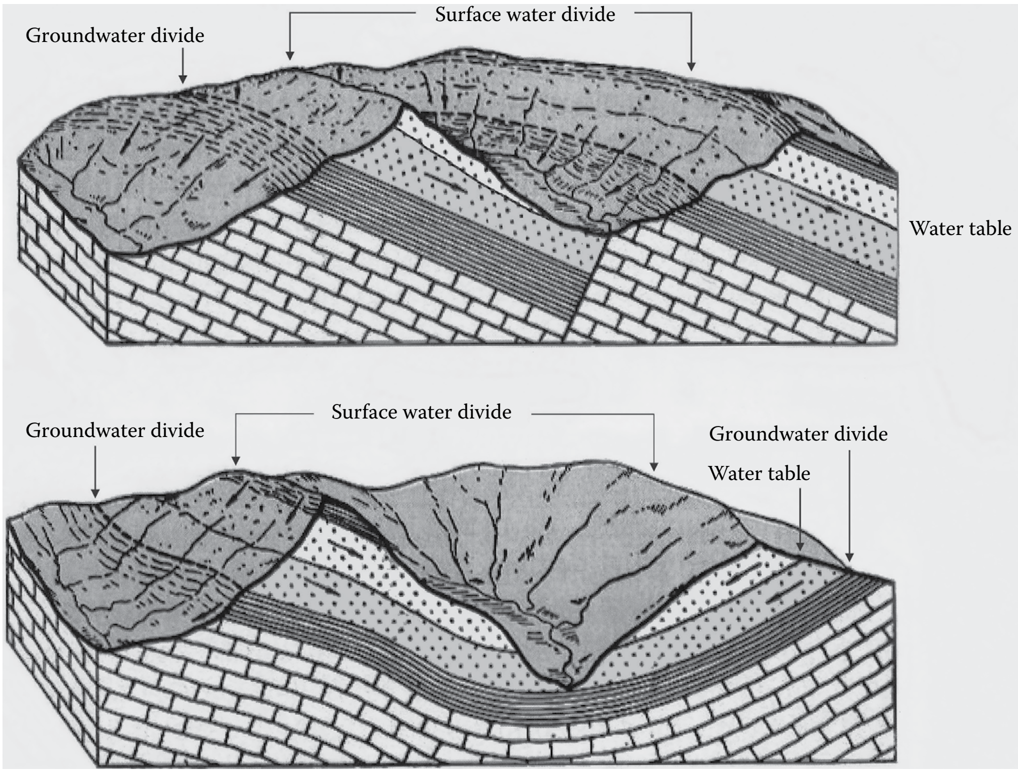

FIGURE 7.2 Surface water and groundwater catchment divide.

extended from the piezometric surface to the underlying freshwater–saltwater interface is balanced by a unit column of saltwater of density ρ_s extended from the same depth to sea level. With reference to Figure 7.3(a), we have

$$\rho_s g h_s = \rho_f g \left(h_s + h_f\right) \tag{7.1}$$

or

$$h_s = \frac{\rho_f}{\rho_s - \rho_f} h_f \tag{7.2}$$

and then

$$h_s = \frac{1.00}{1.025 - 1.00} h_f = 40 h_f \tag{7.3}$$

which is the *Ghiyben–Herzberg equation.* If the water table in an unconfined coastal aquifer is lowered 1 m, the salt interface rises 40 m. The Ghiyben–Herzberg equation underestimates the depth of the interface as the water table is not rectilinear.

Hubbert [57] put in evidence that, for any given water table configuration under hydrodynamic conditions, the position of the interface is given by the intersection of equipotential lines distant Δh on the freshwater table and $\frac{\rho_f}{\rho_s - \rho_f}\Delta_h$ on the interface (Figure 7.3b).

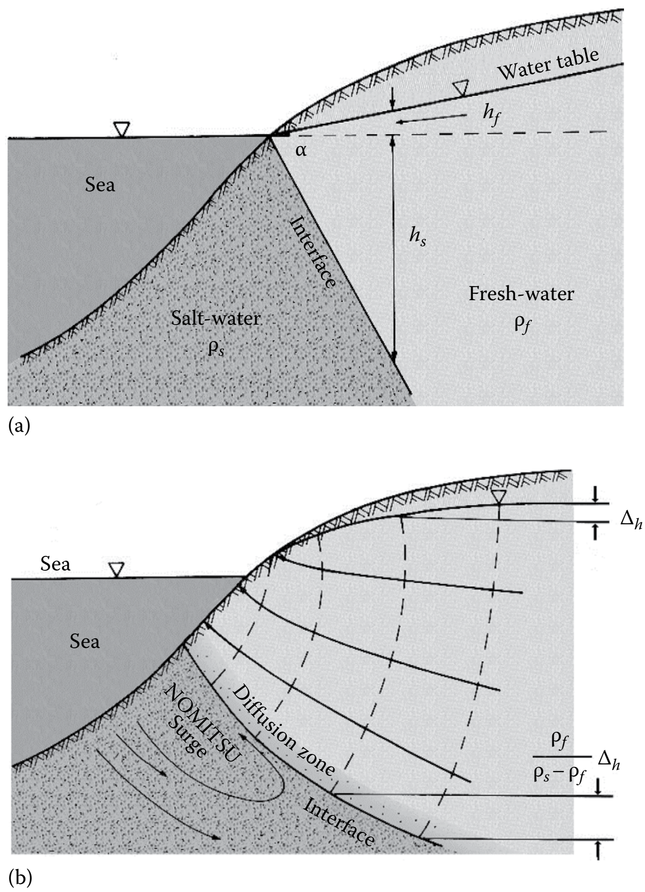

FIGURE 7.3 Freshwater–saltwater interface in unconfined coastal aquifer (a) under hydrostatic conditions and (b) under hydrodynamic conditions. ([a]: From Badon Ghijben, W. and Drabbe, J., Nota in Verband met de voorgenomen Putboring nabij Amsterdam, Tydschrift koninklijk Institute Ing, The Hague, the Netherlands, 1888/1889, pp. 8–22; Herzberg, B., *J. Gasbeleucht.u. Wasserversorg München*, 44(815819), 842, 1901. [b]: From Cooper, H.H. Jr. et al., Sea water in coastal aquifers, Paper 1313C, U.S. Geological Survey of Water Supply, Washington, DC, 1964, pp. 1–84; Freeze, R.A. and Cherry, J.A., *Groundwater*, Prentice Hall, Englewood Cliffs, NJ, 1979; Hubbert, M.K., *J. Geol.*, 48, 785, 1940.)

The interface is not a sharp surface but it consists of a diffusion zone between saltwater and freshwater bodies, of which the salinity varies in space and time depending on hydrodynamic conditions. [18–20,63,73,78].

It is not the objective of this work to give a description of the number of contributions, after Badon Ghijben's, and Herzberg's and Hubert's, to analytically explain the saltwater intrusion process under varying conditions [19,21,49,52,67,84].

The morphology of the interface between surface water, groundwater of different salinity, and the sea strictly depends on the hydrodynamic balance, strongly affected by (1) natural piezometry fluctuations due to natural inflow, runoff, and evapotranspiration; (2) groundwater drawdown, determining upconing and gradient inversion with seawater ingression; (3) irrigation; and (4) sea-level variations due to waves, tides, and climate changes. In coastal areas jeopardized by earthquakes, the interface may be strongly affected by tsunamis and anomalous waves, which cause temporary coast submersion, so that seawater infiltrates and causes groundwater and soil salinization (Figure 7.4).

Frequently, the salinity of brackish waters in coastal karst aquifers is not due to present-day seawater but waters of marine origin long trapped in the solid phase of the aquifers. Chemical and isotope

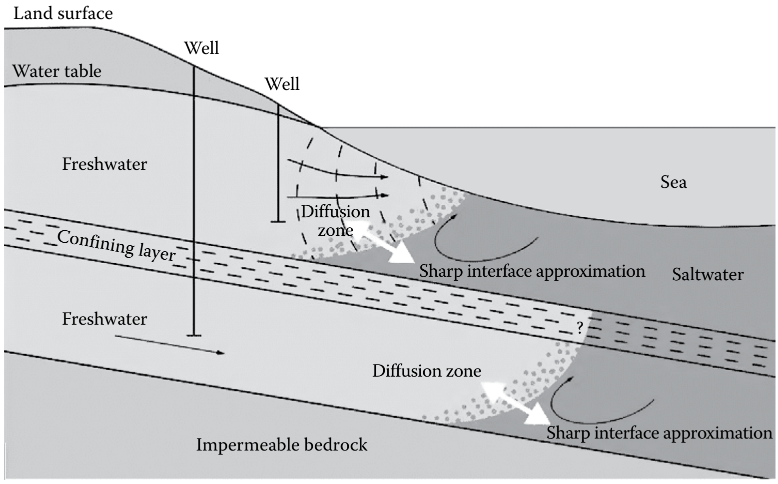

FIGURE 7.4 Water table varies between a maximum and a minimum level depending on freshwater inflow and outflow. Arrows indicate fluid movements. Submarine groundwater discharge (SGD) is driven by convection, hydraulic head, tidal pumping, and wave setup.

characteristics of saltwater sampled inland in coastal aquifers have demonstrated that the salinity of the original seawater intruded in the past could be modified in time by diagenetic processes. Diagenetic water actions can be observed indirectly in mixed waters: their chemical and isotopic characteristics can normally be traced back not only to processes overlapping simple mixing but also to preexisting modifications of the salt end member with respect to present-day seawater [41,98]. Modeling is available to predict long-term behavior of the interface in response to changes in population, water use, and other actions that impact groundwater [15].

Fresh groundwater flow into the sea is generally diffused and can be conspicuous as submarine groundwater discharge (SGD) from submarine springs, as in karstic areas. Thus, it can be well detected by remote sensing and direct observations, and it can be evaluated through a water budget based on observed data (surface runoff, piezometric measurements, pumping tests) [85].

The groundwater recharge is any volume of water flowing into an aquifer over a unit time period, whereas the discharge is any volume of water flowing out of that aquifer over a unit time period:

$$R = P + D \tag{7.4}$$

where

R is the recharge, unaffected by pumping, in [L^3/T]
P is the pumping rate, in [L^3/T]
D is the discharge rate of water (SGD) not captured by pumpage, in [L^3/T]

The *net pumping rate* refers to the water permanently removed from the aquifer, that is, the total pumped water minus the part of the pumped water that returns to the aquifer as recharge.

The water budget between all the inflows, outflows, rates of evapotranspiration, and changes in storage (Figure 7.5) is strongly affected by anthropic activities, mainly by groundwater withdrawals, irrigation, drainage, and urbanization works. Understanding water budgets and how they change in response to human activities is a crucial aspect to be taken into consideration in coastal aquifer management on a sustained basis.

Natural recharge due to replenishment is possible through (1) effective rainfall and snowmelt infiltration; (2) inflow of groundwater from other lateral or lower aquifers, confined in the alluvium or directly

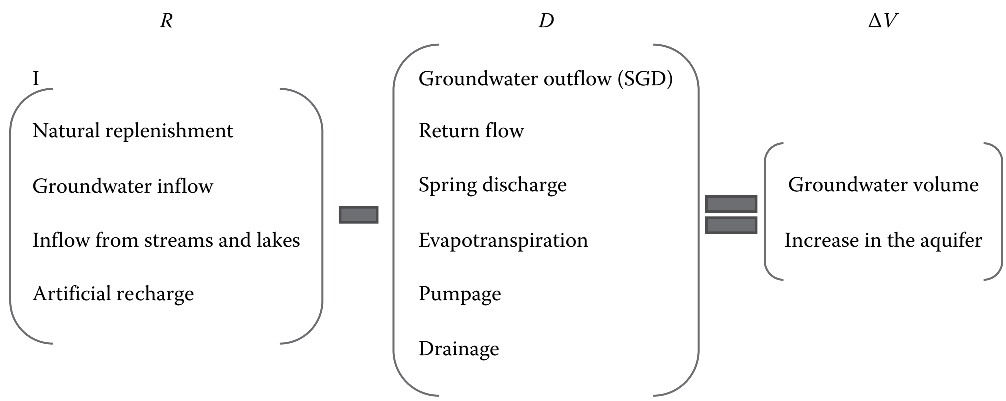

FIGURE 7.5 Coastal aquifer budget.

from the bedrock; and (3) inflow from streams and lakes of different catchments. It may be conveniently integrated by artificial recharge achieved by injecting wells or putting surface water in basins, furrows, ditches, or other facilities, from where it can easily infiltrate into the aquifer through pervious soil [12,31]. Artificial recharge requires a thorough knowledge of the physical and chemical characteristics of the aquifer system and extensive onsite experimentation and tailoring of the artificial recharge technique to fit the local or areal conditions [37,59].

Total discharge consists of natural groundwater outflow in the form of SGD, groundwater return from irrigation and sewage infiltration to the surface, spring discharge, and evapotranspiration, plus pumpage and drainage.

In the case of drought, natural replenishment, due to direct infiltration in the area, is nil. The groundwater inflow, depending on the delay time due to the distance between the recharge and the discharge area, may be such that the maximum groundwater level in the coastal wells is observed during droughts.

The return flow consists of irrigation groundwater not consumed by evapotranspiration but returned to the aquifer. Evapotranspiration, which is water evaporation plus plant transpiration, depends on climatic conditions and type of soil cover.

The volume of fresh groundwater resource, ΔV, is represented by the water volume stored between the maximum and the minimum level of the piezometric surface, whereas the groundwater volume between the minimum level and the underlying freshwater–saltwater interface is the reserve. A persistent recharge decrease strongly affects coastal groundwater quality and its nutrient content, thus impacting associated ecological communities. Sustainability depends on the entire system and concerns the long-term welfare of both humans and the environment [80,81].

7.2.3 Coastal Aquifer Functions

Coastal aquifers are natural reservoirs of groundwater normally consisting of freshwater from natural and artificial recharge stored in effective rock pores, hydraulically connected to the sea and coastal water bodies of different salinity.

Under hydrostatic conditions, pores act as reservoirs, where interactions with the solid phase may develop in time, depending on rock and water composition. Under hydrodynamic conditions, major fractures act as main drains for minor fractures and rock porosity. Groundwater chemical composition variations may be observed in time when pumping.

As far as groundwater flows, aquifers also act as natural conduits from the recharge to the discharge area. Soil and the unsaturated zone, especially in porous media, serve as a filter and purifier for water of degraded quality.

Case by case, the relevance of these threefold functions should be well determined in fractured and karstic aquifers, characterized by a dual porosity, due to major fractures with a higher permeability and high storage, which also act as collectors draining groundwater from intercepted minor fractures with a lower hydraulic conductivity.

According to the dual-porosity model originally developed by Warren and Root [95], a fractured medium is assumed to consist of two interacting, overlapping media: a medium of low intrinsic permeability and high storage (matrix with fine cracks) and a medium of high permeability and low storage (coarse fractures and karstic voids).

Most of the current guidelines to recognize dual-porosity systems from well tests were summarized in type curves for different flow phases, starting in a single porous medium, through a transition zone, and finally through the second porous medium [43]. Pressure drawdown can be broken down into three parts: coarse fractures, fine cracks, and wellbore damage zone. Changes in the hydraulic head due to water withdrawal (discharge from major fractures) or fluid injections would affect the aquifer effective stress, and this, in turn, would influence the fracture hydraulic conductivity.

7.2.4 Safe Yield

Groundwater overexploitation due to intensive agricultural practices, industrial or civilian needs, excavations along river courses, reclamation of land for agriculture and building, and changes in irrigation techniques is causing a progressive depletion of water resources, particularly in areas where the water balance is delicate and at risk [10,71].

The yield of an aquifer is a decision variable to be determined as part of its management. It may vary from year to year depending on water quantity and quality. In a coastal aquifer, the volume of fresh groundwater withdrawn during a certain period cannot exceed its replenishment so as not to endanger water quality.

The *safe* or *sustainable yield* of a coastal aquifer may be defined as the maximum annual groundwater abstraction that will not produce undesired results over time, such as water quality degradation, increased water treatment costs, and rights infringement of other users in the same water system. This definition applied to coastal aquifers better specifies the concept of safe yield, defined as the amount of groundwater that can be withdrawn from an aquifer in the long run without significant ecological impacts [13,23].

In a coastal aquifer hydraulically interconnected with the sea, the average groundwater level is not eventually affected by well pumpage, as far as fresh groundwater depletion is progressively reintegrated with saltwater intrusion, whereas the water table may be strongly affected by reclamation and drainage of coastal wetlands, which help maintain water table levels and keep the interface zone stable. It could be assumed that under hydrodynamic conditions, freshwater is progressively replaced by intruded saltwater. Thus, available freshwater of good quality is progressively mined and reduced in volume, although the pumping rate and hydrodynamic level are maintained indefinitely. The water budget is balanced from the quantity point of view, but not from the quality point of view (Figure 7.6).

Fresh groundwater-level variations cause brackish groundwater upconing and final diffusion zone expansion at the interface, as schematized in Figure 7.7. In the long run, the process of groundwater salination and interaction between the rock (aquifer solid phase) and groundwater of varying salinity may come out to be irreversible for its environmental impacts, even with new freshwater inflow. Interactions between rock and water concern both the emerged and submerged parts of the coast intended as the transition zone between continents and seas.

Freshwater SGD quantity and quality variation may have direct impacts on the nearshore marine environments at the local and global scales. Parameters concerning geology, precipitation, land use, topography, and inclusion/exclusion of recirculated seawater estimates are the main factors necessary for SGD assessment [85]. Gambolati [38] put in evidence the relationship between coastal regression, erosion, and sediment transport in the Romagna coastal region, Italy; the natural subsidence due to deep downward tectonic movements and consolidation of geologically recent deposits; and the anthropogenic land subsidence due to groundwater withdrawal, as well as sea-level rise.

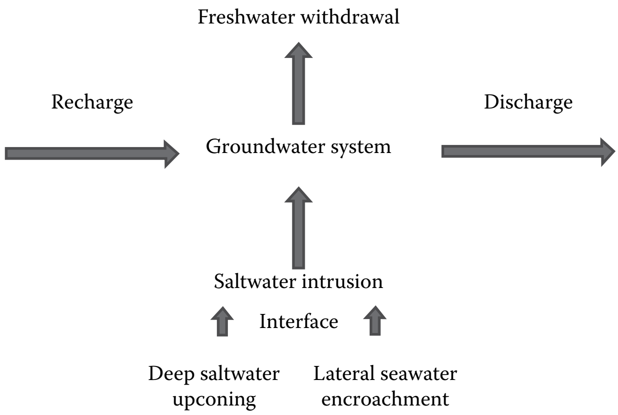

FIGURE 7.6 Fragile groundwater budget in an aquifer system open to the sea. Saltwater intrusion increases with freshwater withdrawal.

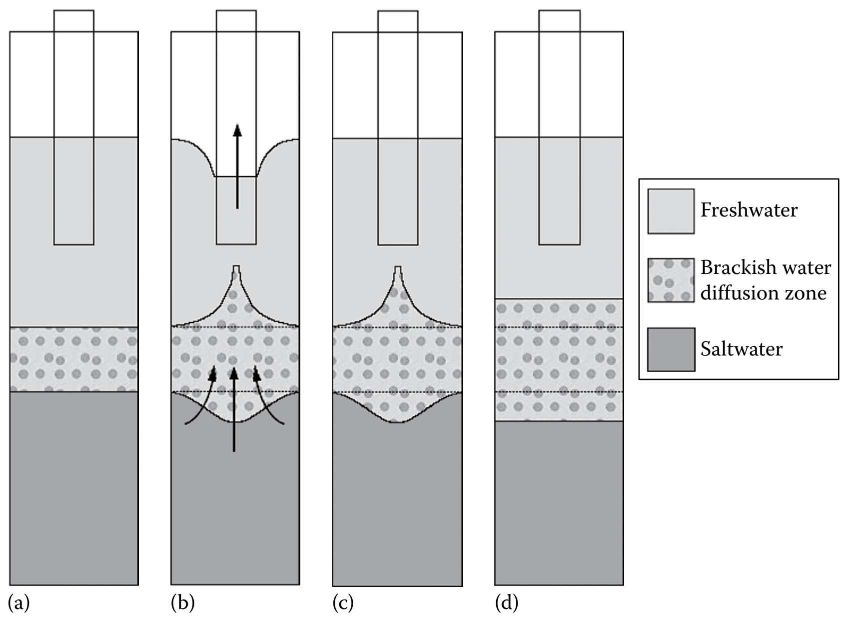

FIGURE 7.7 Water-level variations and upconing in pumping wells: (a) water level under steady conditions; (b) freshwater-level drawdown and brackish water upconing with downward displacement on the bottom of brackish water diffusion zone during pumping; (c) deformation of the diffusion zone persisting after pumping; (d) expansion of the diffusion zone when steady water-level conditions conditions are recovered.

7.3 Groundwater Salination Processes

Saltwater intrusion processes and their effects are quite well known and described in the literature, particularly in salt water intrusion meetings (SWIM) proceedings, available for download (http://www.swim-site.org/). Saltwater intrusion is generally caused by overexploitation, excessive fresh groundwater development with respect to effective natural recharge, land use change, climate variations, and sea-level fluctuations. Short- and long-term climatic fluctuations influence the amount of recharge and, consequently, the groundwater resources available for use [8,32,70,97].

7.3.1 Lateral Seawater Intrusion, Upconing, Saltwater Spray

For the most part, groundwater salination in coastal aquifers is caused by the intrusion of present-day seawater. Under natural hydrostatic conditions, only limited parts of coastal areas may be affected by saltwater intrusion. Under hydrodynamic conditions, in the case of recharge depletion due to droughts or drainage and where coastal aquifers are overexploited, salination is encroaching upon increasingly larger areas. In fact, well pumping in coastal aquifer systems modifies hydrodynamic levels, producing gradient inversion and consequent *lateral saltwater ingression* when the drawdown radius of influence, depending on terrain *K* rate, trespasses the fragile interface between fresh groundwater, coastal saline water bodies, and the sea, far beyond the shoreline, even when aquifer recharge is higher than the yield extracted.

Pumpage also causes *upconing* of seawater trapped in deep layers formed in geological past, such as syndepositional connate saltwater and dense brines, sometimes connected to salt domes, evaporitic deposits in thin beds, or disseminated geologic formations. The upconing of brackish and saltwater, often consisting of fossil waters, causes water–rock interactions that are difficult to control, affecting groundwater quality and aquifer hydraulic parameter values.

Soil and groundwater salination may be due to *seawater spray* and anthropogenic salt released from industries, roads, etc. Coastal aquifers may be particularly endangered by mining activities, industrial facilities, and unsuitable engineering works.

Under natural conditions, sea-level variations due to surges, tides, and tsunamis determine temporary low coast land submersion so that saltwater infiltrates and causes groundwater and soil salination.

Retoxification processes may be observed where there is an accumulation of heavy metals in alluvial deposits. Alluvial sediments act as long-term sinks for large amounts of heavy metals, and through reverse chemical processes, such as desorption and dissolution, they can revert into large sources of heavy metals in a bioavailable form. In estuarine deposits, the trapped heavy metals are released into the water as free ions or as complexes with dissolved organic matter (DOM) and suspended organic matter (SOM) [60,79,83].

Inland pollutants transported by floods partly outflow directly into the sea and are partly deposited with deltaic sediments. Floods and tsunamis may heavily devastate urbanized low coastal areas, where they mobilize pollutants of different diffused and point sources, and thus infiltrate and endanger groundwater and soil, at grades depending on their vulnerability. Interaction effects of salination and pollution, depending on temperature, pH, and Eh (oxidation potential), are not easy to control. Inland pollution of transboundary aquifers, typical of karstic areas like Slovenia, Croatia, Bosnia and Herzegovina, Albania, Greece, Montenegro, Turkey, Israel, Palestine, and North African countries, may affect coastal aquifers, where large volumes of water are discharged from the aquifer system through terrestrial and submarine springs [104].

7.4 Drought Impacts on Coastal Aquifer System Hydrodynamics

Droughts may trigger a series of processes with iterative and reciprocal effects on the emerged and submerged coast (Figure 7.8). Reduced groundwater recharge implies a decrease in fresh groundwater discharge into coastal water bodies and the sea, and this can bring about land degradation, affect productivity potential, cause saltwater intrusion, and endanger productivity activities based on coastal resources development, such as fisheries. The loss of water resources and ecosystem degradation may have adverse economic effects on the sustainable development of urban areas and irrigation water availability, with immediate backlash on groundwater recharge.

Persistent droughts affect the water balance, and as a result, under the new hydrological conditions, current water systems may be insufficient to match the water demand. Such droughts may occur too rapidly to allow manager's reactivity, in both time and information, and require extra plans for crisis management and uncertainties.

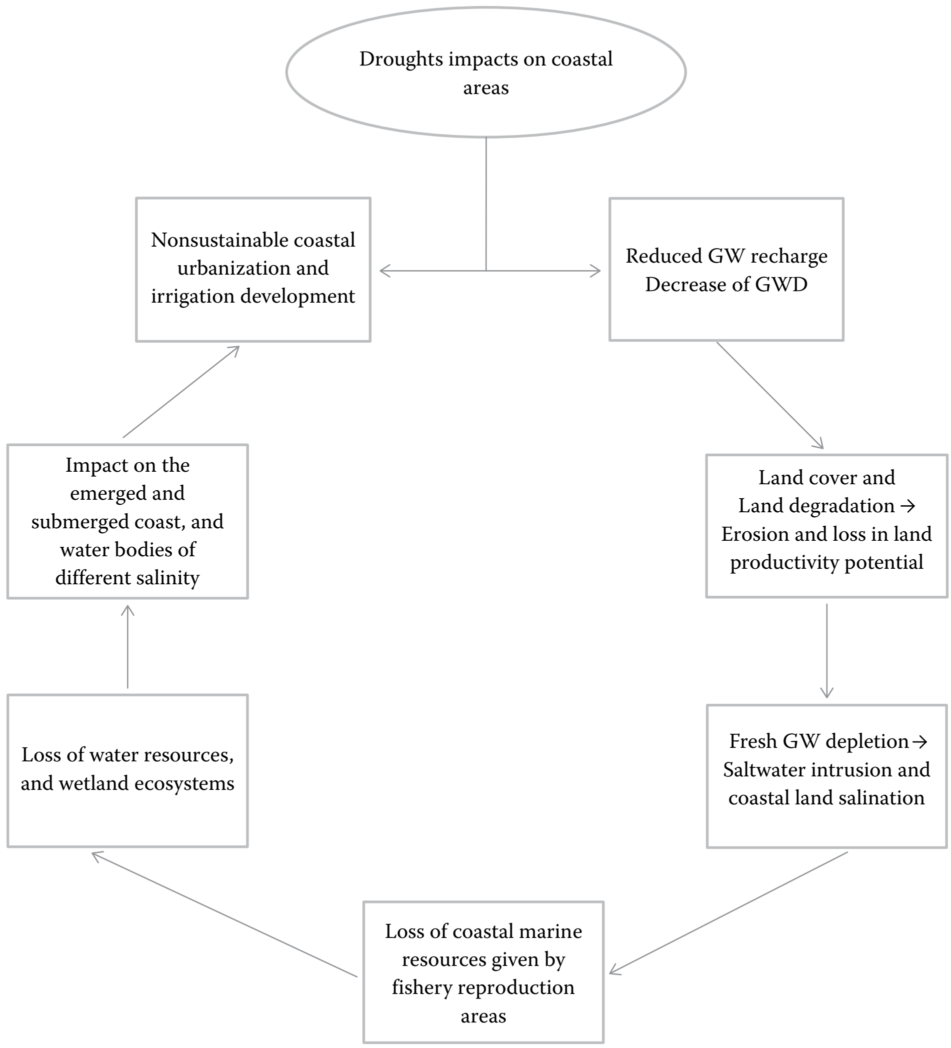

FIGURE 7.8 Drought impacts on coastal land and water bodies.

Sensitivity analyses with different assumptions about potential future conditions are usually performed to account for uncertainties associated with climate change and to allow management adjustments.

Drought effects on the aquifer are delayed in time depending on the travel time needed for the last water infiltrated in the recharge area to flow to the discharge area.

The diminishing discharge of freshwater is conceptually represented by the *recession curve* or falling limb of the hydrograph in the absence of further replenishment when the effective infiltration is practically ended, and the aquifer discharges only its reserves, that is, the water volume, V_f, stored above the diffusion zone interface (Figure 7.9).

It is assumed

- Under steady conditions due to droughts, as freshwater withdrawal is replaced by saltwater, the hydrodynamic water level of V_f remains stable, depending on the rate of pumpage;
- V_f top boundary is determined by the hydrodynamic water level in unconfined aquifers and by the confining layer in confined aquifers;

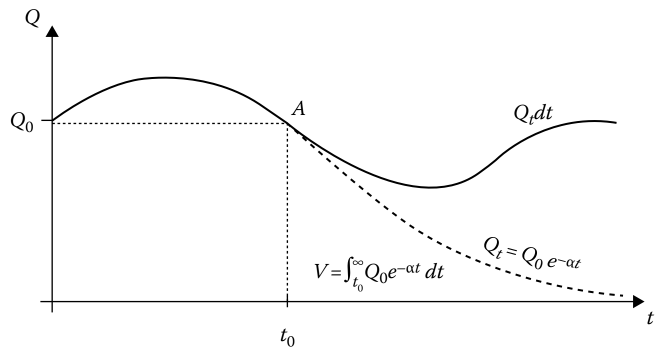

FIGURE 7.9 Groundwater flow recession curve.

- In both aquifer types, V_f bottom boundary is defined by the diffusion zone interface, which expands as a function of the regression coefficient α, typical of the aquifer (independently of groundwater salinity), up to the limit fixed, considering water demand quality requirements for drinking water, irrigation, and industrial purposes, and the environment.

The recession curve may be represented by the simple exponential relation used by Maillet [66] for the discharge of a volume of water stored above its minimal piezometric surface:

$$Q_t = Q_0 e^{-\alpha t} \tag{7.5}$$

$$\alpha = \frac{\log Q_0 - \log Q_t}{0.443t} \tag{7.6}$$

The storage capacity of the reservoir at t_0 may be assessed by considering

$$V = \int_{t_0}^{\infty} Q_0 e^{-\alpha t}\, dt \tag{7.7}$$

By integrating between $t = 0$ and $t = \infty$

$$V = \frac{Q_0}{\alpha} \tag{7.8}$$

and for $t \neq 0$

$$V = \frac{Q_0 - Q_t}{\alpha} \tag{7.9}$$

represents the *dynamic resource* of the water volume V_f stored at t above the diffuse zone interface overlying saltwater. It was widely demonstrated that part or all of the hydrograph recession can be fitted empirically by Maillet's equation [5,55,96]. Boussinesq [11] expressed recession in quadratic form as

$$Q_t = \frac{Q_0}{(1 + \alpha t)^2} \tag{7.10}$$

where

$$Q_0 = \frac{1.724Kh_m^2 l}{(1+\alpha t)^2} \tag{7.11}$$

and

$$\alpha = \frac{1.115Kh_m}{n_e L^2} \tag{7.12}$$

where

K is the aquifer hydraulic conductivity
n_e is the effective porosity
l is the aquifer width perpendicular to its length L
h_m is the initial hydraulic head at distance L
Kh_m is the transmissivity

The recession curve appears to be closer to exponential when the flow has a very important vertical component and closer to quadratic when the horizontal flow is dominant. As a consequence, aquifer permeability anisotropy also changes the recession form. The combined use of the two fitting methods allows one to quantify the thickness of the aquifer under the outlet.

In French literature, the equation of Boussinesq is often quoted as the equation of Tison [88] and elsewhere as the equation of Werner and Sandquist [96]. Maillet's exponential equation gives an approximate analytical solution for the diffusion equation that describes flow in a porous medium, whereas the depiction of base flow recession by Boussinesq's quadratic equation provides an exact analytical solution capable of yielding quantitative data on aquifer characteristics [24,26,33].

7.5 Management Policies

Primary criteria to alleviate pressure on water resources overexploitation, particularly in dry coastal areas, are effective water demand management and water use efficiency, considering climatic conditions and hydrology processes, hydrogeological characteristics, water allocation schemes combining efficiency and equity principles, water supply infrastructures, and needed engineering works.

A common effort is to be made to converge toward common management criteria of sustainable water resources development so as to prevent conflicts among different users. International cooperation is needed for transboundary coastal aquifer management.

Users should be informed and educated to reduce the use of fertilizers and pesticides, and incentives should be given to reduce and displace industrial and agricultural activities from vulnerable areas so as to mitigate their impacts in coastal areas.

7.5.1 Intrinsic and Integrated Vulnerability to Saltwater Intrusion and Pollution

Different methods have been proposed by various authors to assess groundwater vulnerability to nonpoint source (NPS) contamination [3,16,27,34,94]. The most common mapping and modeling methods developed to assist water resources managers during decisions regarding groundwater protection, monitoring, remediation, or sustainable management have been recently reviewed by Gurdak [47].

Georeferenced data on punctual contamination sources (PCS), diffused contamination sources (DCS), contamination preventers and patterns, subjects exposed to contamination risk (targets), and aquifer system flow net may be integrated into a geographical information system (GIS) map-building process of the intrinsic vulnerability assessment and mapping of an area so as to obtain an integrated vulnerability map.

The intrinsic vulnerability is the sensitivity of a coastal aquifer system to degradation due to pollutant percolation and saltwater intrusion. Saltwater intrusion increases vulnerability and may affect the result of aquifer restoration and salinity mitigation actions.

Groundwater vulnerability methods are classified into three groups as follows [44,47,50]: (1) overlay and index methods, such as DRASTIC, GOD, EPIK, and GALIT methods, based on GIS gathering indexes representative of aquifer characteristics; (2) process-based methods consisting of mathematical modeling to approximate contaminant fate and transport; and (3) empirically based statistical methods correlating groundwater chemistry and explanatory variables of the study area with GIS [102], which can represent contaminant spatial variability in updatable vulnerability maps [29,56,60,64,68,74–76,86,87,99,100,104].

Among the overlay and index methods, the widely used DRASTIC [28,46,48] is the acronym of seven indices adopted by the United States Environmental Protection Agency (US EPA) to represent the Depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of the Vadose Zone, i.e., the zone above the water table, which is unsaturated or discontinuously saturated, and hydraulic Conductivity by attributing scores from 0 for low risk to 10 for high risk. The scores are multiplied by an unsaturated depth-zone media and hydraulic conductivity of the aquifer. Groundwater contamination risk is assessed by parameter-specific weight, and then the weighted scores for the seven DRASTIC factors are added to produce the final vulnerability score [50].

The GOD model considers groundwater occurrence and recharge, overall lithology, and depth to groundwater [35]. Unlike DRASTIC, the GOD model also takes into consideration the fractures of the aquifer system.

The EPIK model [27] is a commonly used overlay and index approach for groundwater vulnerability assessments in karst aquifers. EPIK is an acronym for Epikarst, Protective cover, Infiltration, and Karst network development. EPIK is a multiattribute weighting-rating method (i.e., overlay and index) that assesses the groundwater sensitivity of karst terrain [32] and has been used successfully in some karst regions [2,42,62].

The GALDIT method [14] is specific for assessing coastal aquifer vulnerability to saltwater intrusion. Factors, representing measurable parameters available from different sources, are groundwater occurrence (aquifer type: unconfined, confined, and leaky confined) (G), aquifer hydraulic conductivity (A), depth to groundwater level above sea level (L), distance from the shoreline (D), the impact of the present seawater intrusion in the area (I), and aquifer thickness (T). Each of the six parameters has a predetermined fixed relative weight ranging from 1 for the least significant weight to 4 for the most significant one. A rating value between 1and 10 is given to each parameter, depending on local conditions, with 10 representing the highest vulnerability. The local vulnerability index V is obtained by multiplying the rating of each parameter by its relative GALDIT weight and adding all the six products. The higher the index, the greater the seawater intrusion potential.

The concept of groundwater vulnerability, which is used to define the sensitivity to natural and human impacts, may be extended to also consider the sensitivity to the effects of the processes induced by saltwater and drought in coastal aquifer systems, wetlands, and soils. In fact, saltwater intrusion not only causes fresh groundwater degradation, jeopardizes the fragile coastal environment, and activate dramatic changes of wetlands ecosystems, but may also trigger soil salination and saltwater–rock interactions alongwith limestone diagenesis and, especially in loose sediments, adsorption/desorption of pollutants and heavy metals, retoxification, cementation, leaching, and recrystallization. Sediment texture alteration may strongly affect the flow regime. Hydrogeological parameters of an aquifer change by diagenetic processes due to water–rock interactions [41,72,79]. A large number of studies report that the porosity of an aquifer changes in zones of contact between different types of water, resulting in the sediment texture alteration by cementation, leaching, and recrystallization [77].

The GALDIT method does not consider the vulnerability to contaminants. The DRASTIC, GOD, and EPIK methods could also include the following parameters: distance from the shoreline, aquifer thickness, and impact of the present and past saltwater intrusion on rock–water interactions in the interface zone.

Integrated vulnerability zoning and mapping rely on professional judgment to assess weight factors and aggregate point rating [1,75], but are fundamental tools in the iterative process of coastal areas and water resources planning at the appropriate scale.

The scale denominator of the mapping, the frequency of information points, and the number of useful data per point are ruling factors depending on the detail required in planning.

The physical and chemical processes of infiltration, recharge, and contaminant attenuation may be predicted with deterministic models, which give analytical and semi-analytical solutions for predicting and mapping the contaminant spatial development in time in the aquifer system [17,54]. Process-based and statistical methods give reliable results at large scales if available data are sufficient to calibrate and validate the model, whereas they appear to be less rigorous at small scales [45].

To evaluate a model reliability, we should ascertain whether it implements the assumptions correctly (model verification) and whether the assumptions which have been made are reasonable for the real system (model validation). Hence, the usefulness of models as working tools is the ability to reveal a quantitative trend [82,90,91].

Modeling of variable-density groundwater flow in a coastal zone, where the density distribution is nonuniform, has obviously been improved in the past decades. Interface models, solute transport models, were developed in the past decades to represent the transition zone in the aquifer system, in addition to models coping with three-dimensional (3D) transient variable-density groundwater flow, and as computer capacity is increasing, coupled multicomponent reactive solute transport models are increasingly being improved [9,20,22,25,39,40,61,69,70,92,93,101,103]. The reliability of their assumptions will always depend on the data quantity and quality [82,90,91].

However, vulnerability assessments are important tools for water resources managers and policy makers to prevent groundwater resources degradation.

7.5.2 Groundwater Protection Zoning

Given their situation, coastal areas are sensitive to pollution, contamination, and instability due to sea-level variations and erosion. Thus, they should be, as far as possible, protected from overdevelopment and misuse because of their recognized natural, ecological, and cultural values.

Particular safeguard rules should be adopted in the interface zones between surface water and groundwater of different salinity as they are vulnerable to freshwater exploitation and droughts, of which the effects in time should be monitored to plan the best mitigation actions. In the case of transboundary aquifers, overlapping multiple countries, coastal protected areas should be recognized, dedicated, and managed, through legal or other effective means, to achieve long-term conservation of nature with associated ecosystem services and cultural values [82]. Safeguard systems vary considerably between countries, depending on national needs and priorities and differences in legislative, institutional, and financial support.

7.6 Coastal Groundwater Resource and Reserve Assessment

The freshwater volume V_f and regression coefficient α are among the parameters to be taken into consideration when defining coastal aquifer vulnerability parameters as they express how the freshwater volume decreases in time with regard to the water demand. In the case of severe droughts, the effective infiltration in the recharge areas is to be considered null or severely reduced, and as freshwater is progressively replaced by saltwater, only the groundwater recharged by the last effective rainfall is available.

If fresh groundwater is not sufficient, it has to be integrated with surface and nonconventional water resources, especially recycled and desalinated water.

Wastewater treated according to local requirements, so as not to endanger the environment, may be conveniently stored and used for irrigation and certain industrial and civil uses [71]. Recycled water allows farmers to plan ahead and not be limited by water shortages. The demand for water reclamation is increasing, and modern treatment methods can prevent adverse effects on human health and on the environment [51].

Different policies are adopted for water desalination. Desalination methods, based on inverse osmosis, may be the only solution to grant water supply, especially in small islands with scanty freshwater resources. Some desalination plants are functioning in all arid coastal areas for the production of drinking water, mainly to match the demands of tourist resorts and to cater under emergency drought conditions. However, the use of desalinated water is hardly affordable for irrigation without incentives. Production costs are variable, depending on local energy costs. In some countries, desalination plants are not favored by local rules on account of the impacts on coastal marine ecosystems due to the brine released into the sea and on account of the soil salination caused by saltwater upconing when tapping saline groundwater from coastal aquifer wells.

7.7 Groundwater and Integrated Water Resources Management (IWRM)

Coastal areas are particularly vulnerable to drought effects. Thus, water resources and soil should be managed in an integrated way. The concept of integrated water resources management (IWRM) implies the sustainable use of available groundwater and conventional and nonconventional surface water to meet effective water quantity and quality demand of all users and to preserve water resources and reserves as fundamental ecosystem components, considering the water balance of hydrogeological catchments, different areas interested in water use, and supply costs.

In areas jeopardized by drought, IWRM aims at (1) identifying the most significant problems and short-term and long-term strategies to diversify the water sources needed to match the water demand; (2) protecting the quantitative and qualitative status of water resources, and introducing use efficiency measures to reduce water losses and wastes, regulate consumption, control pollution, and monitor and manage surface water reservoirs; (3) listing and analyzing ongoing regional and national processes, initiatives, criteria, projects, and remedial actions developed in similar coastal dry areas to respond to water issues; (4) inducing stakeholders' participation and information exchange and raising public awareness of the value of water and the need to save it; and (5) educating users, in addition to providing incentives, to reduce the use of fertilizers and pesticides and displace industrial and agricultural activities from vulnerable areas so as to mitigate their impacts on coastal areas.

Drought effects may be predicted and prevented. Water authorities and land administrators should agree to find the best fitting method to manage land and water resources in an integrated way so as to prevent conflicts among different users through policies and implementation mechanisms that transcend artificial administrative boundaries. International cooperation is needed for transboundary coastal aquifer management as it requires an integrated vision of hydrogeological characteristics, climatic conditions and hydrology processes, water allocation schemes, supply infrastructures, and needed engineering works.

Freshwater of best quality should be reserved for drinking purposes. Agricultural practices should make more use of recycled and brackish water for irrigation, the only means available in areas with scanty water resources, considering real, free global market requirements, as in the long run, producers might not be able to rely on high public incentives. Aquaculture may be developed depending on water quality and different types of fish exigencies. Industries may conveniently recycle their water, at least for the most part.

Coastal aquifers are strategic but vulnerable groundwater reservoirs that are to be assessed through continuous monitoring and developed very carefully, considering the amount and quality of water available from changes in groundwater recharge, discharge, and storage for different levels of water consumption.

Trade-offs are required to avoid conflicts among different water users, taking into account resource availability, effective needs, priorities, and socioeconomic conditions. System-wide hydrologic analyses of groundwater and surface water resources are commonly used to simulate the response of the system to various development options and provide insight into appropriate management strategies [58]. However, an evaluation by water management professionals is required to appraise model simulation results and plan appropriate actions.

Adequate information is a prerequisite to succeed in groundwater management. Groundwater management has to be a continuous process in which technology and education improve solidarity and participation of the stakeholders and enable a more efficient use of the resource. There exists a consensus that, to avoid conflicts and move from confrontation to cooperation, water development projects require the participation of social groups affected by the project, that is, the stakeholders.

The participation should begin in the early stages of the project and should be as much as possible, bottom-up and not top-down. Current information technology allows information to be made available to an unlimited number of users easily and economically. IWRM and coastal zone management criteria should be based on the assessment of the integrated vulnerability to contamination and saltwater intrusion, and on 3D modeling simulations validated with field data collected by monitoring systems, so as to zone protection areas available for different uses (Figure 7.10).

Monitoring carried out using direct and indirect methods is essential to determine and predict groundwater deterioration and assess other management activities in coastal aquifers. Problems should be tackled and solved at different suitable space and time scales.

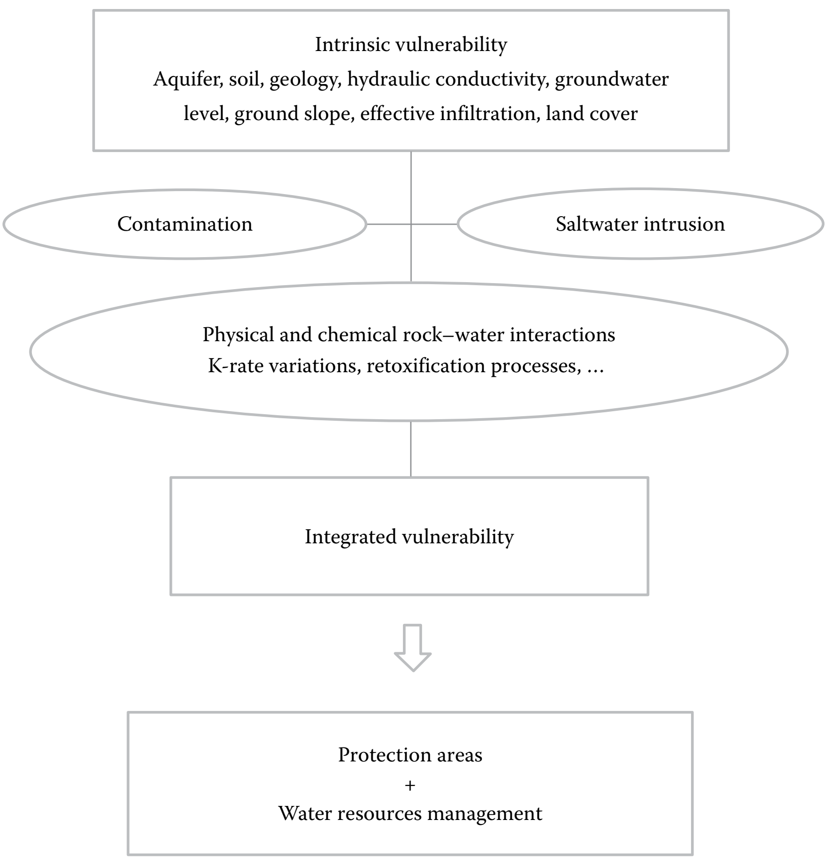

FIGURE 7.10 Vulnerability assessment and 3D modeling finalized to zone protection areas and define coastal areas and sustainable water resources management criteria.

The management of coastal waters and areas requires interdisciplinary collaboration among different experts on water resources and land planning, agronomy, biodiversity, economy, and water laws and directives. Promotion of joint management of shared aquifers is a need.

7.7.1 IWRM Policies

Floods, typical of surface water in arid and semiarid areas, may be conveniently moderated by stocking the excess water in reservoirs upstream of coastal areas so as to (1) mitigate excessive erosion effects and prevent damages downstream; (2) integrate that water with groundwater to match demands for different uses, when and where necessary; (3) guarantee the minimum river outflows needed to counteract surface seawater intrusion in final river stretches, which might induce downward saltwater movement into unconfined aquifers; and (4) produce hydroelectricity.

The water supply system might need to be reorganized so as to face emergency situations. Considering the local delay time in aquifer recharge, groundwater should be preferably used in dry periods, when it reaches its maximum level.

However, erosion cannot be completely blocked upstream without endangering coastal plains and beaches, whose dynamic stability depends on continental water outflow and sea movements, especially in deltas. Upland river channel fragmentation by dams and water regulation resulting from reservoir operation, interbasin diversion, and irrigation affect river discharge and aquifer recharge.

Groundwater offers the advantage that it can be extracted close to the place of final use, but some problems may arise due to its intensive use without public control, such as freshwater reserves depletion, interface land subsidence, contaminant mobilization, and impacts on aquatic ecosystems. Most of these problems can be avoided, corrected, or at least mitigated with an adequate control planning.

The following criteria should be adopted in groundwater planning: (1) the mean rate of groundwater extraction should not exceed the safe yield, that is, of the recharge; (2) the volume of freshwater in storage should be great enough to ensure that no saline groundwater reaches the well screens; (3) risk of (2) must be acceptable only under extreme circumstances; and (4) environmental impacts such as the effects on vegetation and soil must be acceptable.

The following measures are advisable for managing groundwater:

1. Reduction of pumping rate or time-share pumpage from some wells
2. Relocation of wells or redesigning of the well field
3. Reconsideration of land use type
4. Hydrodynamic water level, depending on aquifer exploitation rate
5. Adoption of economic measures for overpumping and overuse
6. Adoption of different pricing scales for domestic, industrial, and agricultural consumption
7. Recharge of aquifers with surface water stocked during rainy periods
8. Sealing of major fractures and damming of karst outlets to control freshwater runoff
9. Use of pressure hydrodynamic barriers, perpendicular to flow lines, by injecting treated wastewater into wells, upstream of the interface, so as to build up a sufficient head of freshwater to block saltwater encroachment
10. Use of depression hydrodynamic barriers by extracting saltwater from scavenger wells before it reaches freshwater supply wells so as to prevent saline water upconing through interface hydrodynamic stabilization
11. Combination of (9) and (10)
12. Use of physical barriers consisting of diaphragms obtained by grouting, slurry walls, or sheet piles, to block shallow lateral saltwater intrusion
13. Plugging of abandoned wells, which can act as a conduit for leaking saltwater from the saline aquifer into fresh aquifers

Physical barriers may be a convenient alternative to depression hydrodynamic barriers, especially in main fractures and freshwater karst outlets, and in cases where there is no freshwater available to be injected, but they are not a common approach.

Physical barriers offer the advantage of not requiring the ordinary maintenance costs of the hydrodynamic barriers of freshwater to block seawater encroachment. In porous media, their construction may be expensive, depending on the grouting needed to build a tight diaphragm and the impact they may have in both the solid and the liquid phase of the aquifer, especially in the case of no recharge, as freshwater could be the only overflow and there would be no flow below the minimal water head surface. Each of these methods can only be applied to specific situations, and the method used will depend on the problem to be solved.

Natural recharge may be conveniently integrated with diffused and intensive artificial recharge, which is recommended when freshwater is available in reservoirs as a reserve for future use during periods of high demand. Artificial recharge is increasingly used for short- or long-term underground storage, where it has several advantages over surface storage, and for water reuse.

Different cases may be foreseen for a reasonably predictable dry period:

1. The permissible fresh groundwater extraction V_f is sufficient to match the ordinary water demand for a limited predictable drought period as the regression coefficient α is low.
2. The freshwater volume V_f is sufficient to match the ordinary water demand, but on account of the high K rate of the aquifer, the regression coefficient α is so high that V_f is rapidly depleted.
3. By lack of continuous natural recharge, V_f is insufficient to match groundwater demands.

In case (3), the recharge can be increased by proper land use and by artificial recharge if the permissible fresh groundwater extraction is insufficient to meet the water demand. Provided surface water is available, the recharge should be increased if more groundwater is to be extracted, and the losses by the outflow of fresh groundwater to the sea should be reduced either by using hydrodynamic barriers or by increasing the recharge.

Possible actions are conditioned by the availability of surface water stocked in artificial reservoirs to recharge aquifers. Monitoring programs are needed (1) to predict the long-term behavior of the interface in response to changes in population, water use, and other actions that impact groundwater and (2) to provide timely information on the existing conditions and a reasonably accurate assessment of interface changes and to dynamically monitor groundwater migration.

The selection of alternative solutions typically involves making complex trade-offs and their economics remain subject to local conditions. Multicriteria evaluation techniques have proven to be an excellent decision support tool for evaluating IWRM alternatives [65].

Models are required to consider the influence of these decisions on flows and downstream water availability, as well as the influence of flows on the productive, passive use and environmental values of water. Delineation and monitoring of saltwater intrusion rely on field observations; numerical modeling takes observation results as constraints for boundary and initial conditions when tackling a particular problem. For control and prevention of the intrusion, practical engineering works are needed, based upon the situation estimates from delineation, monitoring, and simulation.

7.8 Summary and Conclusions

The general characteristics of coastal areas and coastal aquifers were taken into consideration, focusing on the drought effects on saltwater intrusion and pollution processes.

Coastal aquifers, representing the main sources of available freshwater, are at risk of degradation, especially in deltas, where population density in urban areas and straggling settlements is often highest and pollution due to agriculture and industry may be very strong. As far as possible, fresh groundwater is to be considered a strategic resource, especially for drinking purposes, whereas surface water, treated used water, and desalinized water may be allocated to meet other user demands.

Prevention and mitigation measures may be adopted to prevent groundwater degradation. Conflicts among different users cannot be rationally and effectively solved using only technical remedies aimed at controlling saltwater intrusion due to upconing and lateral inflow from the sea.

Monitoring carried out using direct and indirect methods is essential to determine and predict groundwater deterioration and assess other management activities in coastal aquifers.

All available groundwater and surface water sources are to be managed, considering land capability/susceptibility and human resources in an integrated way, so as to grant a real, sustainable economic development for inhabitants of present coastal areas and for future generations.

A common effort is to be made to converge toward common management criteria of sustainable resource development, considering different scenarios in time under local conditions, so as to prevent conflicts, often due to overexploitation and mismanagement of resources.

The integrated management of surface water, groundwater, and biotic and abiotic environmental components is essential to prevent and mitigate interest conflicts between residents of hydrogeological catchments and outside resource users.

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8

Drought Management for Landscape and Rural Security

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Abstract Water resources are most indispensable for global management capacities combined with the need of sustainable, protective use for a most possible reduction of negative impacts to environmental and landscape resources in rural places. Water is a life enabling, protecting, and life creating resource. Therefore, while using the resource, it is essential to acknowledge the ecosystem services implementing standards of life quality, securing human wealth and health as well as securing individuals and communities' landscape and rural environment.

Managing drought and therefore water resources for landscape and rural security is most important as already nearly 2 million people live on the 40%–41% of the total global land mass that is dry. It is estimated that 10%–20% of these dry lands have already been destroyed and are turning into deserts. Regions in Africa, south of the Sahara, and South Asia are facing extreme poverty and hunger.

The changing structures, values, identities, and functioning of landscapes and rural places, such as ecological sustainability and balance, are some of the results that lead to less secure water conditions, which is part of the discussion of this chapter. Next to this, the evolving challenges of further unsecured conditions in the standards of social, economical, cultural, ecological, and environmental life have to be directly correlated to purposes of landscape scale, regional level, and rural security, which will be highlighted in this chapter.

Within the possibly happening tremendously destructuring processes of drought and further on processes to arid and desertificated land compared to regions worldwide, developing as well as developed countries have to fulfill in greatest engagement the aims of United Nations Convention to Combat Desertification (UNCCD) until 2018 and beyond. The topic of this chapter is how to proceed in planning and management for fulfilling these aims of UNCCD in a most optimized way. So, it is getting possible to secure the worlds' landscapes and rural security as being the agars liquor for an enduring sustainable future of human beings and life on planet earth—the one.

8.1 Introduction

In this chapter, we aim to summarize the state of scientific knowledge on drought management within the constellation of landscape and rural security [20]. We explore the current stage of understanding of drought as well as its extent and possible solutions.

We will argue that drought is one of the world's most pressing environmental problems in combination with the impacts of climate change and other pressures. This topic is gaining in global awareness: drought appearance shows how important water resources are for social human interactions, the existence of natural life, as well as for the earth's system cycle as a whole [3,60]. Water resources are most indespensible for global management capacities combined with the need of sustainable, protective use for a most possible reduction of negative impacts to environmental and landscape resources in rural places [3,59]. Water is a life enabling, protecting, and life creating resource. Therefore, while using the resource, it is essential to acknowledge the ecosystem services implementing standards of life quality, securing human wealth and health as well as securing individuals and communities' landscape and rural environment. The key understanding regarding drought appearance is its impact on the natural and social dimension [102], specifically at the landscape scale and regional level.

The management of drought requires the understanding of being the first stage of development for possibly reaching land degradation or even desertification. It also demands a definition of "drought" as defined by Wilhite [102], "drought is an insidious natural hazard that results from a deficiency of precipitation from expected or 'normal' that, when extended over a season or longer is insufficient to meet the demands of human activities and the environment." According to Nandargi et al. [57] drought may lead to desertification or aridity if it persists for a prolonged period accompanied with destructive land use practices [57]. According to Warren and Khogali [99], drought occurs when the moisture supply is abnormally below average for a period of up to 2 years.

Drought normally appears within climate responses and is a divergence from the normal climate [24]. It has to be acknowledged that drought by itself is not a disaster [102], but indices's of a disaster may be observed in the rate of impact on local people and the environment [102]. The land surfaces in the world are divided by geographical, political (state boundary) conditions, and within climate zones and regions. Especially these climatic influencing land surface conditions are one of the most critical and potential influences for population distribution, settlement, urbanization, and agricultural development [34]. Directly or indirectly drought appearance is related to life and livelihood, water, air, and food, which are the basic requirements of civilization, rural as well as urban; and agricultural cropping patterns are totally dependent on water availability and quality [2,18,20]. Looking back at the evolution of civilized urban districts and cities, the importance of water supply, the amount, availability, and quality becomes obvious: within this historical viewpoint of strategically placing urban areas or settlement structures near to rivers, lakes, or fountains, human civilization was able to secure environmentally its survival, habits, handicraft, agriculture, and hygiene or medicinal purposes. The importance of high-quality natural resources and other environmental media like soil, air, climate, and biotic existence and evolution is also obvious: soil development and fertility development, for example, are both dependent on the water supply and the quality of surface and groundwater [2,18].

The impacts of aridity and land degradation affect nearly 2 million people living on 40%–41% of the total global land mass that is dry already [4]. It is estimated that 10%–20% of these dry lands have already been destroyed and are turning into deserts. Regions in Africa, south of the Sahara, and South Asia are facing extreme poverty and hunger.

Landscapes and rural areas are becoming highly disturbed while being threatened in the context of land degradation by intensified land use, reduced groundwater accessibility, reduced precipitation to under 250–80 or even 0 mm/year, as well as water scarcity and aridity in general, resulting in the desertification of dry lands in the long run. But it has to be emphasized that drought is not to be equated with aridity or desertification: aridity is a dominant feature of dry regions, which refers to the permanent condition of low average precipitation or the destruction of available water. For precising the difference between drought, land degradation, or desertification, the terms next to the already described one of "drought" should be clear: "land degradation" in general describes surface decomposition in productive dry lands. Degradation of land resources is one step before desertification. It may lead to desertification of an area, which in its place was not compulsorily an arid region earlier. Desertification is a form of land degradation in arid, semiarid, and dry wet–dry areas, which results from different factors including climatic changes and human activities [89]. In 1949 the term "desertification" was used for the first time in west Africa by the French forester Aubréville [89], whereas in 1972 the term was adopted by the United Nations Conference on the Human Environment (later UNEP) and in 1977 the first world map of desertification was drawn up in Nairobi. In this process, up to 1977, desertification was realized for the first time as being a continuing worldwide process.

Desertificated dry lands are located in the cold, hyperarid, arid, semiarid, dry subhumid, and humid climate zones. Often on the fringes of deserts lying dryland areas are geographical and climatic regions with possibly higher insecurities in sorts of an intensification of poverty and a further possible sprawl of desertification. Also it has to be stated that each insecurity parameter of temporary drought appearance, land degradation, or desertification is forcing (by being linked to) poverty more negatively [2,18]. This status is easily confirmed by the fact that 90% of dry lands and deserts are located in developing countries. Securing poverty reduction, sustainable land use and drought management, mitigation, and adaptation to climate change means the combating of desertification, which affects 61 million km^2 of dryland with a greater part of it already including desertificated land masses. It also implies securing the ecological, economic, social, cultural as well as environmental, and human health and wealth of landscapes and rural places [70,72].

The management of drought requires the observation of multifarious interactions between the different social, ecological, economic, cultural, land use, and legal and political systems, as well as its pressures and drivers. In this chapter, the strength of landscape assessment on regional scale will be apologized for integrating into drought management purposes. The better management option for a holistic and strategic intervening will be the regional level in order to stabilize landscape and rural security in combination with environmental as well as regional development demands. Following one of the excellent results at the Rio Summit, the United Nations Convention to Combat Desertification (UNCCD) [87], land degradation in correlation to scarce water availability, deserting land, and drought has to be effectively minimized in some of the most vulnerable ecosystems and affected populations in the world [87].

The changing structures, values, identities, and functioning of landscapes and rural places, such as ecological sustainability and balance, are some of the results that lead to less secure water conditions, which is part of the discussion of this chapter. Next to this, the evolving challenges of further unsecured conditions in the standards of social, economical, cultural, ecological, and environmental life have to be directly correlated to purposes of landscape scale, regional level, and rural security, which will be highlighted in this chapter.

In order to combat the possibly for ecology, economy, society and culture happening tremendously destructuring processes of drought and further on processes to arid or desertificated land in regions worldwide, developing as well as developed countries have to fulfill in greatest engagement the aims of United Nations Convention to Combat Desertification (UNCCD) until 2018 (Post UNCCD 10 Year Strategy) and beyond. Simultaneously, a global warming has to be limited to a 1.5°C rise and needs to be supported strongly within the framework convention of the UNFCCC (comp. COP 21 in 2015, held in Paris). The topic of this chapter is how to proceed in planning and management for fulfilling these aims of UNCCD in a most optimized way. So, it is getting possible to secure the worlds' landscapes and rural security as being the agars liquor of life "for an enduring sustainable future of human beings and life on planet earth—the one" [70,72].

8.2 Landscape Approach and Rural Security against Drought

Rural landscape development and changing factors are directly dependent on the environmental and landscape-water balance [73], drought appearance, other multi-scaled impacts, and climate change. The offset of drought is climatic instability that can happen in all climatic zones worldwide. Drought slowly continues and accumulates its impacts across a vast area as it is influenced by climatic fluctuations over an extended period of time [18], as compared with other natural hazards like floods and hurricanes which develop quickly and end within a short period of time. The affected—mostly vast—area, which then disturbs rural wealth and security as well as landscape security, is widespread [18]. The consequences are to be seen for years after the end of the drought. Disturbances and impacts through drought appearance are to be seen in the changing micro- and macro-climate, soil degradation, loss of crops, loss of economic activities, starvation or malnutrition, loss of biodiversity, and the spread of diseases [2]. As drought, water availability and quality, as well as soil quality and structure, are next to the other named causes directly influencing rural agricultural crop production and rural employment creation, some further consequences (Figure 8.4) are similar to general climate change syndromes: induced challenges for human life, security, all spatial planning activities, and the intangible as well as tangible faces of our landscapes [70,72,73]. An optimized water table, despite the prevention of drought, is also most important for the survival of species, habitats, and ensuring landscape and ecosystem stability as well as for the production of agriculture [73] and food security [20,21,27]. The extent—interesting for an integrative view of landscape, land use, and water cycle–related change—has to include sociological impacts on rural cultures and the sort of push and pull factors throughout changing systems, which provide more pressure for the migration of rural people into urban areas [73].

Within this perception and observation, a direct constellation of the factors that provide rural security becomes obvious. Until the Madrid Action Plan [89], regional sustainable-economy cycles in Man and Biosphere Reserve inhabiting regions were in some regions (comp. Spree Forest Region in Section 8.4.1) and should be one of the main parts to be supported to a higher gradient: in regions the proper functioning of the ecology and ecological awareness combined with economic wealth is strengthening rural security and in specific might diminish drought appearance within securing rural regions [73,92]. The IPCC [29] "Summary for Policymakers" validates the combined earth system and economic wealth influence consistently, which counteracts the correlation with regional prosperity: the IPCC [29] Fifth Assessment Report (AR5)—the second installment released in Tokyo at the end of March 2014—states that "the incomplete estimates of global annual economic losses for additional temperature increases of around 2°C are between 0.2% and 2.0% of income (± one standard deviation around the mean)" with the risk of higher rather than lower losses (IPCC [29], p. 19). The report then proceeds: "Losses accelerate with greater warming, but few quantitative estimates have been completed for additional warming around 3°C or above" (IPCC [29], p. 19). Constraining warming to 2°C based on the current CO_2 emission path and the installed fossil fuel energy infrastructure base seems to be almost impossible (IPCC [29], p. 19). So a by climate change and other global change syndromes insecured development path for the world, its landscapes and rural regions with many inhabited future risks is the result.

From the global up to the regional scale, aridity zones can be defined by using a variety of approaches including drainage characteristics (de Martonne and Aufrere, 1928), vegetation types (Shantz, 1956), and climatic characteristics (Penck, 1894) [89]. For observing the extent of drought appearance and the impacts on the security of rural regions a holistic approach is needed, which includes the detailed approaches and methodologies mentioned earlier: a modern landscape approach following Reinstädtler [72] will help in achieving prosperity for regions in a sustainable manner and in combination with sustaining landscapes in general. This, in the holistic way of perceiving things, creates more secured circumstances against negative impacts such as drought and other impacts that disturb rural security; water stress or less qualitative (ground) water would also affect landscapes regarding their biodiversity.

8.2.1 Landscape Approach for Landscape and Rural Security

The (cultural) landscape approach and scaling significance has been emphasized already [70,72] by the inclusion of cultural landscapes as being of outstanding universal value on the World Heritage List and the Global Strategy formulated in 1994 [77].

The initiative for including cultural landscapes as world heritage site (WHS) and for enhancing the Global Strategy and linkage between the two was provided by living cultures, in particular traditional settlements and sites [77]. Especially in condensed European areas, the significance of strong linkages between the living culture, the sites, and natural, abiotical, and biotical circumstances in landscapes is obvious. As Marc Antrop [5] states concerning the development of European landscapes in a social context: "Conditions like those in Europe could be the best to test models because, e.g., European landscapes are the result of consecutive reorganizations of the land for a long time to adapt uses and spatial structures to meet changing societal demands" [5].

The intended landscape approach is guiding into a specific development and scale perception [70,72]: the observation and verification in context of drought and climate effective spatial planning should be fostered through the landscape approach and scale with special focus on cultural landscapes [70,72]. Observing, analyzing, and assessing at the (natural or cultural) landscape scale are synonymous with the level of landscape planning and instrumentation [70,72]. Landscape planning comprises analyzing for protection, maintenance, and development, as well as for recreational aspects of nature, culture, land use, and landscapes [70,72]. The similar protective objectives and focal analyses become more clear by introducing the term for specifying the sort of approach required: "Cultural Landscapes—cultivated terraces on lofty mountains, gardens, sacred places …—testify to the creative genius, social development and the imaginative and spiritual vitality of humanity. They are part of our collective identity" [91]. Within the definition of cultural landscapes following Carl Sauer ([77], p. 46), the dependencies and significance of climate change [70,72] and other disturbances or impacts on the natural, environmental system, such as the drought phenomenon for landscapes, become even more obvious: "the cultural landscape is fashioned out of the natural landscape by a culture group. Culture is the agent, the natural area is the medium, the cultural landscape is the result (Sauer [77], p. 46)." When defining the term "landscape" the approach becomes more obvious and inhabits two distinct ways of thinking, the holistic and the analytical approach:

1. Holistic thinking, which is primarily gained through experience, inhabits a dialectical approach, accepts contradictions, and integrates multiple perspectives.
2. Analytical thinking, which isolates the object from its broader context, concerns categorization and predicting events based on intrinsic rules.

The research status of the correlation between landscape approaches in general and environmental security is acknowledged in an important notification by World Commission on Environment and Development (WCED) [100]: "The whole notion of security as traditionally understood—in terms of political and military threats to national sovereignty—must be expanded to include the growing impact of environmental stress—locally, nationally, regionally, and globally."

Combining the local and regional level with environmental stress shows in accordance with Reinstädtler [70] the need to assess environmental and landscape resilience for an improved stress resistance at the landscape scale. Within this background of resilience and improved stress resistance, we are also aware of the need to correlate the environmental combined landscape with rural security as being one status of managing modern twenty-first century landscapes as well as environmental changes at the landscape scale [73].

In this section, landscape values and types of landscapes are proved as assessing instruments of landscape planning. They are in combination with other needed detailed parameters—guiding into the landscape approach and the importance for rural securities management against drought. Specifically, landscape values can at best be understood and integrated in the rural and landscape security context. Preserving rural security and better drought resilience needs flexible planning mechanisms and also transforming processes: a greater potential for transforming planning and management aspects for a more sustainable development are to be seen in landscape planning and the types of landscapes. Diversified types of landscapes create their own specific values, services, and interwoven spheres [14]. Acknowledging the different sorts of landscapes in Figure 8.1, and the diversified values behind them, have to be seen as instrumentations for better management and to be implemented in all upcoming transforming processes of rural development and security purposes.

Figure 8.1 shows general classifications of landscapes and their values or functions with diverse landscape values or functions directly fitting to rural conditions and their rural landscape values and ecosystem services. So the different landscape functions, implemented values, and ecosystem services support in ways of planning the inclusion of the most effective aspects of our physical, social, ecological, economic, technical, and cultural environment [71,73]. The research and planning fields of landscapes support and catalyze functioning ecological, social, agricultural, and life systems [71,73]. Sustaining landscapes enhance in an interdisciplinary way the functioning and valuing of the ecological balance, social abilities and security, physical health and the food supply, economic, commercial, and service functions, as well as the enduring cultural heritage [71,73]. These objectives have to be included in the spatial rural, landscape as well as in regional planning. Figure 8.1 embraces these functions and values as well as the correlations of biotic and abiotic factors, which landscape characters, landscape values, and ecosystem services depend on [71,73]. A small number of abiotic factors influence a large number of biotic, cultural aspects, and by implication vice versa [71,73].

In some of the most common functions, values, and parts of ecosystem services, the outstanding and wide-ranging relevance of the term "landscape" can even be evaluated in terms of its sustaining ecological, resilient, cultural, social, and economic assets and also in terms of its abiotic and biotic correlations and

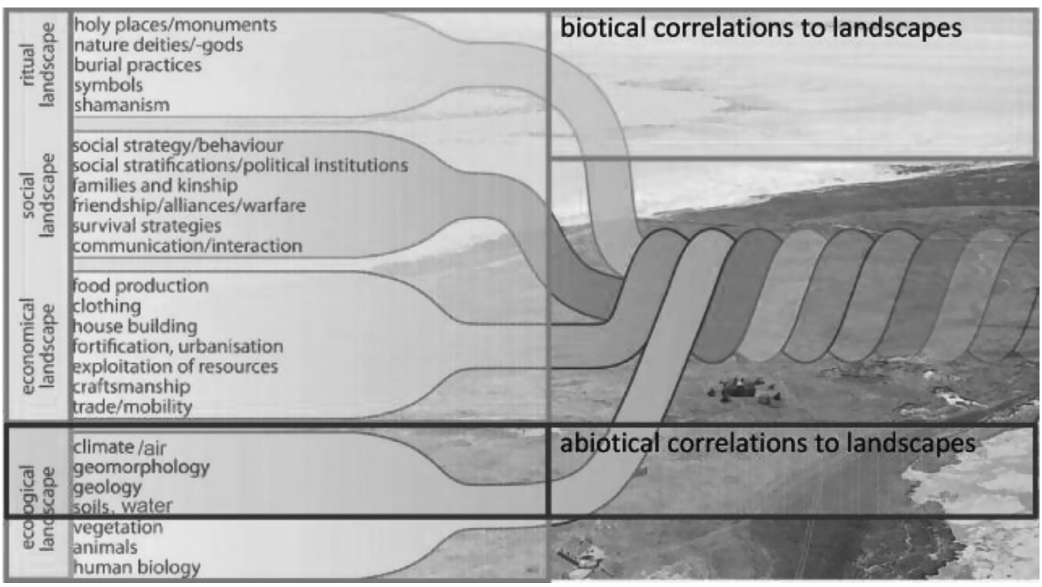

FIGURE 8.1 Different interwoven spheres in a landscape. (From Dieterich, H., Scheme: Different interwoven spheres in a landscape, Accessed March 10, 2011, online available: http://www.uni-kiel.de/landscapes/school/abb/cluster2-1200.jpg, 2011; Slightly modified by Reinstädtler, S., Sustaining landscapes—Landscape units for climate adaptive regional planning, in *Conference Presentation and Proceeding of Abstracts of the International World Heritage Studies* (*WHS*)—*Alumni—Conference*, *World Heritage and Sustainable Development*, June 16–19, 2011, IAWHP, Cottbus, Germany, Online publication: http://www.iawhp.com/wp-content/uploads/2012/01/IAWHP2011_Book-Abtracts.pdf, 2011, p. 18; Reinstädtler, S., Sustaining landscapes—Landscape units for climate adaptive regional planning, in *Conference Proceeding of the International World Heritage Studies* (*WHS*), *World Heritage and Sustainable Development* June 16–19, 2011, published in 2013, IAWHP, Cottbus, Germany, Online publication: http://www.iawhp.com/wp-content/uploads/2013/05/World-Heritage-and-Sustainable-Development-_-IAWHP-eV_2011.pdf, 2013, pp. 45–65.)

legally protected goods and media [71,73]: the abiotical ones are expressed by the term "ecological landscapes," inhabiting the environmental media of climate and air, soil, water, geomorphology, and geology [14,71,73]. The biotic components of ecological landscapes are vegetation, animals, and human biology. Biotical components in valuing landscapes also contain the terms "economical landscapes," "social landscapes," and "ritual landscapes" [14] (Figure 8.1). Economical landscapes in a balanced state retain food security, clothing, house building, fortification and urbanization, exploitation of resources, craftsmanship, trade, and mobility for society. Social landscapes promote social strategies and behavior, social stratifications and political institutions, families and kinship, friendships, alliances, warfare, survival strategies, communication, and interaction. Within ritual landscapes holy places and monuments, nature deities and nature gods, burial practices, symbols, and shamanism are implemented [14] (Figure 8.1).

The diverse perspectives and scales to be focused on within the construction of landscapes have no single natural scale where landscape assessment is being observed. The range of spatial, temporal, valuing, and organizational scales in landscape systems and its research is obviously wide [8] and thus predestined for implementation in planning for rural-related optimization in general [71,73] and for preserving rural security against drought appearance in particular.

8.2.2 Sustaining Landscapes in the Context of Combating Drought and Desertification

Environmental and related landscape changes directly correlate with qualitative and quantitative, spatial and structural, changes in the environment, landscapes as well as ecosystems [71,73]. They later imply considerations of the main pressures and driving forces [71,73]: drivers like enhancing, shifting, and varying land use concerns, globalization pressures and dynamical processes in general, together with the influences of current political restrictions or spatial planning procedures—all are combined with more uncertain parameters of climate change risks [71,73]. These are some of the impacts foremost influencing the modern landscapes of the twenty-first century, which have to be acknowledged in the context of sustaining grade and resilience as well as reflecting the challenges in landscape change and the term "cultural landscapes" in general [71,73].

Drought appearance, land degradation, and desertification processes are not to be underestimated in terms of their impact on landscape development, its security, as well as for the social security and the anthropocentric viewpoint on outreaching economic values: there is mounting evidence that dryland degradation and competition over increasingly scarce resources can bring communities into conflict [4]. Drought is definitely of limited appearance in time, but even within short disturbances it is able to create long-lasting impacts: drought disasters—which are occurring more often at the same localities—influence soil consistency, crop amount, and other environmental media degradation and cultural life. Furthermore, people whose livelihoods and survival depend on already arid regions "are swelling the ranks of environmental and economic refugees who are testing the already stretched resources of towns and cities across the developing world" [4]. So the damage to economic development is correlated less to social, environmental, landscape, and rural security. For example, economic development is exceptional, such as the drought in China in 1984 which cost approximately USD13.8 billion, in Zimbabwe in 1982 which cost USD2.5 billion, and in Brazil in 1978 which cost USD2.3 billion [88]. But the developed countries and states are already facing the challenges of drought impacts [103], which show up in the economic statistics for the state of Washington [104]: agriculture is the industry most heavily affected, followed by food securing. The food and agriculture industry in the state supports more than 180,000 jobs and generates 13% of the state's economy [107]. Of the harvested crop land, the 27% that is irrigated produces nearly 70% of the state's crop value (USD3.6 billion) [107].

Next to drought, land degradation and desertification are important negative impacts to be defined in terms of land, land use, and other environmental, economic, or cultural changes at the landscape scale.

Figure 8.2 shows the theoretical climatic scenario and changes of land use, landscapes, and agricultural crops in every region of the world with nonirrigated land where drought might appear. The drought

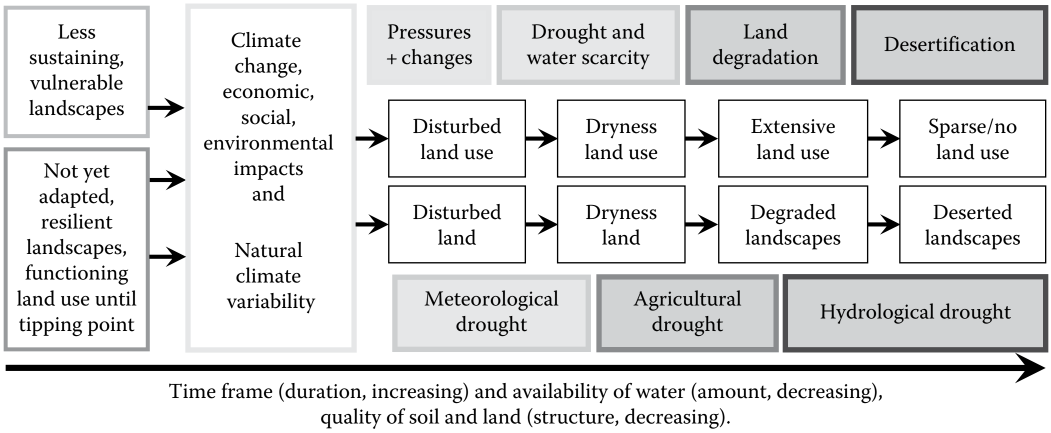

FIGURE 8.2 Development chain of correlation between water availability and landscape sustaining and resilience grade. (After Reinstädtler, S., Sustaining landscapes—Landscape units for climate adaptive regional planning, in *Conference Presentation and Proceeding of Abstracts of the International World Heritage Studies* (*WHS*)*—Alumni—Conference, World Heritage and Sustainable Development*, June 16–19, 2011, IAWHP, Cottbus, Germany, Online publication: http://www.iawhp.com/wp-content/uploads/2012/01/IAWHP2011_Book-Abtracts.pdf, 2011, p. 18; Reinstädtler, S., Sustaining landscapes—Landscape units for climate adaptive regional planning, in *Conference Proceeding of the International World Heritage Studies* (*WHS*), *World Heritage and Sustainable Development*, June 16–19, 2011, published in 2013, IAWHP, Cottbus, Germany, Online publication: http://www.iawhp.com/wp-content/uploads/2013/05/World-Heritage-and-Sustainable-Development-_-IAWHP-eV_2011.pdf, 2013, pp. 45–65; Wilhite, D.A. et al., *Weather Climate Extremes*, 3, 4, 2014; NDMC, Status of state drought planning, USA, Accessed July 24, 2014, online available: http://drought.unl.edu/portals/0/docs/10StepProcess.pdf, 2013.)

prone area is correlated to the three different stages of drought: (1) meteorological drought, (2) agricultural drought, and (3) hydrological drought. The starting point of the scenario is that the less sustaining and more vulnerable a landscape is, so the less resilient is the landscape to drought, which equalizes to less-adapted land use. Land use activities; other culturally driven activities; climate change pressures; economic, social, or environmental impacts; natural climate variability; and climatic, biotic, and abiotic conditions in general all disturb the landscape and land use. The impacts have accelerated the totality of soil that is bare and open to wind erosion during the dry seasons. The continuous reduction of topsoil through erosion due to poor conservation practices provides grounds for the reduction of vegetation cover and, when the soil below the topsoil is solidified, most of the rainfall water runs off into waterways. The dryness and drought reduces vegetation cover, which continues along with a reduction of water recycling and monsoon circulation (if the concerned region is in a monsoon area). Thus continuous decline, dryness or even degraded land (scapes), and a predestination for or appearance of an agricultural drought stage might go hand in hand in this scenario with land use changes and damages of agricultural crop productions. The last stage of the micro-scale scenario (Figure 8.2) and its development chain in water scarcity depicts the hydrological drought with desertification, in total deserted landscape and sparse, only irrigated or none land use existing.

So, desertification stands in the row of the last stage of fragmentation stage of rare functioning environmental media (Figure 8.2). From the perspective of landscape development, the sustaining or resilience grade of landscapes deserted landscapes with rare or none land use can be found within desertification land. The resulting stage of the water scarcity development chain depends on the extent and frequency of drought appearance. Drought at the beginning of the fragmentation period may lead into land degradation and then up to deserted land with no environmental buffer anymore (Figure 8.2): desertification is hard to invert, but it can be prevented [4] or mitigated. Protecting and restoring arid regions will not only alleviate the growing burden on the world's urban areas, it will also contribute to a more peaceful and secure world [4]. Protecting and restoring for a sustainable future for landscapes has to begin not only with the first appearance of drought in land areas, but before when an area is signaled up as drought endangered, which is so-called preventive or risk management [103] and not merely crisis management. So the preventive mission has to be brought forward for more resilient and therefore sustaining landscapes and ecosystems. This would also support the preservation of landscapes and cultures that date back to the beginning of civilization and which are an essential part of our cultural heritage [4].

So the climate scenario (Figure 8.2) shows that within drought management initial environmental and therefore landscape changes have to be implemented for the better protection, prevention, and adaptation against drought and desertification processes. While preventively assessing a landscape and its drought affinity, the resilience grade of a landscape gives the parameter for drought affinity with including the climatologically characteristics in general. This combined land use perspective of sustaining resilient grades of a landscape [71,73] is easily applied within combined water and soil management options. Nevertheless, intensive field research in the verification of this hypothesis has to be forced and brought forward. Landscape and land use planning have the greater advantage for being integrated disciplines, which is very important for protection against aridity and proper drought management.

8.3 Drought Combined Rural Landscape and Environmental Security Assessment

The opposite of drought means to have a functioning water security [20,21,27]. Water security is defined "as the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socioeconomic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability" [85].* Many factors, such as the biophysical, infrastructural, institutional, political, social, and financial, contribute to water security and many lie outside the water realm. Therefore, interdisciplinary collaboration is required across sectors, communities, and political borders so that competition or potential conflicts can be solved [85].

The characteristics of a region with water security [85] are as follows:

- Good governance with adequate legal regimes, institutions, infrastructure, and capacity in place.
- Transboundary cooperation with sovereign states that discuss and coordinate their actions to meet the varied and sometimes competing interests for their mutual benefit.
- Economic activities and development, which are characterized by adequate water supplies that are available for food and energy production, industry, transport, and tourism.
- Populations have access to safe, sufficient, and affordable water to meet the basic needs of drinking, sanitation, and hygiene; to safeguard health and well-being; and to fulfill basic human rights.
- Ecosystems are preserved and can deliver their services, which both nature and people rely on, including the provision of freshwater.
- Populations, which are so far resilient to water-related hazards (including floods, droughts, and pollution) and climate change, are giving a counteracting force against these water-related hazards and climate change.
- Peace and political stability avoids the negative effects of conflicts, including reduced water quality and/or quantity, compromised water infrastructure, human resources, related governance, and social or political systems. Water security requires collaboration across sectors, communities, disciplines, and political borders. It means reducing the risk of potential conflicts over water resources, between sectors and between water users or states.
- Financing involves the facts that innovative sources of financing complement funding by the public sector, including investment from the private sector and micro-financing schemes.

* UN-water supports the inclusion of water security in the post-2015 development agenda as part of the Sustainable Development Goals. Compare: www.unwater.org; www.unwater.org/water-cooperation-2013.

These UN [85] stated characteristics of water security show that water is central for achieving a greater sense of security, sustainability, development, and human well-being. Landscape and rural security have their roots within the development of the concept behind environmental security, which is best described by Petrosillo et al. ([52], p. 13) and laid out by Müller et al. [55] who defined these techniques:

- Landscape identification and characterization, providing the basic and initial information of the area in question
- Land cover change detection and analysis of landscape dynamics, providing information about the changes of important landscape features in time
- Landscape indicators, providing important and representative variables for the aggregated characterization of landscape structures and functions
- Landscape theory, providing basic ideas and concepts for an improved understanding of landscape development and potential vulnerabilities and risks
- Landscape scenarios and modeling, providing a synthesized understanding of structures and processes and delivering basic information about management consequences for decision-makers
- Landscape assessment and adaptive management, providing concepts for evaluation and manipulation of landscapes in an iterative manner (Müller et al. [53]; Petrosillo et al. [56], p. 13).

Insufficient water resources are a challenge to security purposes for landscapes, rural areas, and the sectoral water security [20,21,27] itself: approximately 700 million people in 43 countries are already inconvenienced by water scarcity and drought. Long-term average evaluations are illustrating the situation and status [19,22,32]. And as drought may lead to desertification or aridity if it prevails for a prolonged period and is accompanied with destructive land use practices [57], the different stages and parts of a proper drought assessment are the most important.

So, the objective of this section is to understand the assessment forms and possibilities, distribution, and utilization patterns for drought and water scarcity while correlating water scarcity and climate change to rural landscape and environmental security. The environmental, social, and economic effects of these processes have to be redirected effectively with having flexible assessment methodologies and planning instruments. Flexible means in sorts of assessment methodologies and planning instruments that they are able to identify the more vulnerable or resilient areas even when climate change or global change–driven planning processes are giving instable evaluation situations. The results should lead to carrying out effective measures. Water deficiency is typically assessed by hydrologists looking at the population–water equation. The first one by Falkenmark and Lindh [22] proposed an index that defines water stress as occurring when annual water supplies drop below 1700 cubic meters per person, which means absolute scarcity.

One-third of the worldwide population already lives in dry lands. So, qualitative assessment and resulting planning frameworks have to be brought forward: these proper planning outlines have to contain recommendations against drought sprawl combined with adaptation suggestions against climate and global change syndromes. As a study by Cook et al. [11] states, a warming climate may spread drying to a third of the earth's land surface. Drought and also desertification phenomena are calamities that critically disrupt regions and people's quality of life worldwide, including especially in Africa, the Mediterranean, the U.S. Corn Belt, and parts of Asia [11,103]. The researchers [11] stated that dry zones in especially Central America, the Amazon, and southern Africa will grow larger. The European summer aridity of Italy, Greece, Turkey, and Spain [89] is expected to extend farther north into continental Europe [11]. These defragmenting processes should be assessed through landscape assessment for preserving landscape, rural, water, and environmental security. Water security should have implemented landscape resilience and the support of proactive as well as preventive measurements. Also the correlation and communication of the different stakeholders and their responsibilities or pressures, which emerge from the appearance of drought, have to be fostered through landscape planning instruments, drought management, and Integrated Water Resource Management (IWRM). Lowered food and ecological security or economic loss due to climate change are key areas of observation and directly relate to drought. With the example of agricultural purposes, drought is strongly related to moisture deficits for the vegetation during the growing season. Up to that drought can result next to food insecurities in the loss of jobs for many plant workers in farms and manufacturing [104]. So, climate change and relating droughts might cause huge annually monetary loss especially for the farming industry. For agriculture, the moisture balance in the soil is the important parameter. Farmers also will not be able to plant crops anymore that season [107]. After a declared drought the later question arises: how to manage all these impacts as they affect nearly everyone: diverse stakeholders and concerned people in the nation, state, region, or commune and at the household level [107].

Initially, the stage of drought intensity has to be made clear. As a consequence of the usual hydro-meteorological variability, drought occurs in general in four different grades of intensity:

1. *Meteorological drought*. Parameters are natural climate variability and precipitation deficiency in amount, intensity, and timing. The first impacts of this stage of drought are a reduced runoff, infiltration, deep percolation, and groundwater recharge. Increased evaporation and transpiration may result. Despite these impacts, a second impacting step with high temperatures, high winds, low relative humidity, greater sunshine, and less cloud cover may also lead to increased evaporation and transpiration [65,93].
2. *Agricultural drought*. This parameter is especially about a soil quality and water deficiency, which impact plants in sorts of water stress and reduce biomass and yield—depending on the sorts of investigated land use in a landscape—with being followed by the hydrological drought [63,90].
3. *Hydrological drought*. Parameters are reduced stream flow and less inflow to reservoirs, lakes, ponds, and wetlands. These processes might signify in the long row also the disturbance, disfunctioning, or loss of habitats such as wetlands and others. The loss of wildlife habitats characterizes the last step of intense of drought [63,90] and the beginning of land degradation and desertification processes.
4. *Socioeconomic and cultural drought*. Parameters are socioeconomic activities and dynamic trends and actions. In different parts of the world, the community and its activities are hampered due to climatic conditions and a scarcity of water supply. Drought and high temperature are also accelerated by the speed of cultural activities.

The next important thing to understand is the complexity of interaction within climatic interdependences, the characteristics of environmental medias, hydrological cycles, and local as well as regional land constellations, which combine land use and landscape structures. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) in 2007 predicted that the increased warming of the earth will lead to more evapotranspiration and an enhanced capacity in the atmosphere to hold moisture, as well as extreme weather events, such as floods [43]. According to the hydrological cycle there will be less precipitation, especially in tropical and subtropical dry lands [83]. Droughts will be longer as well as also more intense in such regions, and new areas will suffer from drought [83]. So it has to be stated that for counteracting drought a proper assessment has to be done. For assessment purposes, three essential characteristics of drought—intensity, duration, and spatial coverage—are differentiated based on appearances [93].

In evaluating drought and especially degradation or even the desertification process [86], description is very important [86] and uses the parameters listed earlier. Based on these descriptions and diverse investigations, methodologies for counteracting drought problems can be hypothesized, acknowledging the interaction between physical soil degradation and social consequences, poverty and drought affinity or even desertification [86]. But demarcation of drying areas next to desertification areas is difficult as quick changes happen within. That is why metering over a long period of time is recommended for a best evaluation of results for demarcation lines of drying areas [86].

Within the examples of the IPCC [43] and the study by Cook et al. [19], the importance of a proper assessment of hydro-climatic characteristics in drought appearance might be further described as one where many regions around the world may be at greater risk of drought by 2100 as warmer temperatures wring more moisture from the soil [19]. The IPCC [43] also warns that soil moisture is expected to decline globally and that dry regions will be at greater risk of agricultural drought. It also predicts a strong chance of soil moisture drying in the Mediterranean, the southwestern United States, and southern African regions [43], which is consistent with the latest modeling comparisons and results of the climate dynamics study [19], which finds that—through rainfall changes alone—12% of land will be subject to drought by 2100 [19]. For climate modeling and projections, not only is the precipitation grade relevant, but also the heat factors and resulting higher evaporation rates [19]: drought appearance will spread to 30% of land when higher evaporation rates from the added energy and humidity in the atmosphere are considered [19]. Even regions like important wheat, corn, and rice belts in the western United States and southeastern China, which are expected to get more rain, will be at risk of drought because of an increase in evaporative drying [19].

In context of drying land and being extremely important for further discussion the definition of aridity should be mentioned: aridity is equal than a deficit of humidity. So, precipitation is lower than the evaporation in arid areas. The aridity grade gives information for the predestination possibility of drought or degradation. Degeneracy and magnitude of water scarcity are the depending parameters. The aridity grade, and with it the possibility for drought or degradation, is measurable over the aridity index (AI) [86]. The AI is a numerical indicator composed of precipitation divided by (active and passive) evaporation for estimating the grade of aridity [86]. AI quantitatively—and since the twentieth century also empirically—defines the degree of dryness of the climate at a given location. With some specific sort of AI index it is also possible to describe a species distribution. For example, determining the degree of aridity with an AI higher than 1.0 within monthly metering means to obtain the aridity in this perimeter of monitoring. Next to AI the medium annual precipitation and the medium annual evaporation are important for evaluating dry lands, arid regions, or areas [86]. In order to estimate the grade of affinity for a drought-prone area, these forms of metering are helping in assessing drought. But these indices are limited in using only climatic data. They are excluding the use of soil data [14] but it must be acknowledged that these indices are limited to using only climatic data and not soil data [14].

Coming back to the prior discussion: if precipitation is the only thing under consideration, then the great agricultural centers of the western United States and southeastern China would not be considered at risk of drought [19]. Projections of both rainfall and evaporative demand were analyzed by Cook et al. [19], with the result that increased evaporative drying will probably tip marginally wet regions at midlatitudes, like the U.S. Great Plains and a band of southeastern China, into aridity [19]. So most models have focused to date on precipitation as the principal driver of drought. Cook et al. [19] give greater emphasis to the measurement through evaporation and the more technically, potential evapotranspiration (PET) in drought. Through better modeling of this PET, 43% of the global land area will experience significant dryness by the end of the twenty-first century [19]. This is about 20% more drought-prone land masses than it was predicted by models, which are principally looking at precipitation alone: involving the precipitation parameter alone would have meant to have calculated only 23% of affected land masses worldwide [19]. These results show how in-depth qualitative assessment may work for more calculable results of area spread and occurrence of drought for better risk management preparation of these complex mechanisms in times of climate change. Therefore, the significance of a chosen scale for evaluating and managing different assessment purposes in the field of climate change has already been verified by different case studies [2]. When selecting criteria for successful adaptation, then factors of influencing adaptive capacity, calculating indicators, and the scale of observation are of greatest interest for efficient solutions [2].

Other important assessment stages for further hydro-climatic evaluations are

- Adaptation measures against drought appearance have to be identified in accordance with its severity in different crop seasons [78].
- Remote sensing analysis has to be done for further validation of the selected drought vulnerable areas by, for example, if available, moderate-resolution imaging spectroradiometer (MODIS)* satellite image or similar sensors like the advanced very-high-resolution radiometer, called ENVISAT-MERIS [54,79].

* This is a payload scientific instrument that was launched into earth orbit by NASA in 1999 on board the Terra (EOS AM) satellite and in 2002 on board the Aqua (EOS PM) satellite. The instruments capture data in 36 spectral bands at varying spatial resolutions. Together the instruments image the entire earth every 1–2 days. They are designed to provide measurements of large-scale global dynamics including changes in the earth's cloud cover, radiation budget, and processes occurring in the oceans, on land, and in the lower atmosphere. Highly processed products such as vegetation indices are also available through MODIS; see MCST webpage: http://mcst.gsfc.nasa.gov/ ("MODIS Terra Satellite Images"). ucar.edu (National Center for Atmospheric Research: Earth Observatory Laboratory); retrieved January 7, 2011.

- MODIS products or other methods have to be integrated into the field of landscape combined drought assessment land cover, leaf area index, fraction of photosynthetically active radiation, gross primary productivity, albedo, burned area, surface reflectance, land surface temperature and emissivity, normalized difference vegetation index (NDVI), enhanced vegetation index, thermal anomalies, and fire [54].
- Global, national, and regional collection of information for drought and also combined degradation and desertification [89].
- Open access for universities, institutions, ministries, schools, libraries, and international conferences [89].
- Collection of climate model simulations like those already completed for the IPCC's 2013 climate report [103].
- Drought metric formulations [103].

Also risk assessments for better drought preparedness have to be implemented, such as the Washington State Department of Agriculture (WSDA) risk [107]:

- Proofing the state water right with being divided in a junior or senior right for the concerned area and the sort of domestic or production purposes.
- The stability of the water level when using a well.
- If the availability of the current needed water supply is reduced, the possibility of access to an alternative water supply should be checked. Or a plan to reduce the water use and to match the supply should be developed.
- Receiving space through allocation at a creek, river, etc., and up to that additional information on the own water supply. Also the information of alternative water sources including the use of an emergency well could be interesting.
- Implementing measures to conserve water such as
    - Enclosing irrigation ditch lines in pipes
    - Converting rill irrigated fields to more efficient systems
    - Reusing plate cooler water for livestock watering or other uses
    - Cutting back on landscaping that requires lots of water
    - Only running dishwashers when full
- Evaluation of own facility for fire risk, establishing fire breaks, reducing fuel loads, and taking other appropriate measures.
- Existence of state and federal programs that may be available to address the economic impacts of drought [107].

Assessment for drought also means evaluating soil degradation with analyses such as soil infiltration, soil compaction, the soil stability method, and cesium 137 in erosion and deposition analysis. Further storing of (any) data and information, evaluating them, comparing and monitoring them should be fostered. Meteorological datasets with a higher spatial density of the area of interest and for a time period over years needs to be available and should be required for qualitative evaluation. For this storage of knowledge, data, information, and metering platforms or data storage systems are needed, which are for example in the form of Geographic Information System (GIS)-data storage systems as organized by United Nations Environment Program (UNEP) [89], as well as the following datasets and acquiring rules:

- The Global Assessment of Human-induced Soil Degradation Database (GLASOD), which is used globally as well as in Africa (with a higher resolvent form) [89].
- The Assessment of the Status of Human-induced Soil Degradation in South and Southeast Asia, mostly used in South and Southeast Asia [89].

- Saha et al. [78] suggested the development of a national drought information system (NDIS) as a framework based on five key components, which act as an effective tool for designing an integrated adaptation option menu at the national level. NDIS will be a complete resource for [78]
  - Adaptation related to drought
  - Compiling a trace of every individual adaptation tool, research, and studies in the agricultural field related to drought
  - Providing input and acting as a catalyst for field-level demonstrations of viable adaptation options with the potential to improve the capacity of rural livelihoods to adapt to climate change
  - The overall adaptation strategy that focuses on minimizing the overall production risk or loss.
- The analysis findings have to include the NDVI within a drought year as it may have a mean NDVI less than the long-term mean NDVI for dry seasons (which depends on the location that may be continental or regional, or on the scale).
- The Standardized Precipitation Index (SPI) analyses has to be done to find the historical profile of drought. Through SPI analyses, it can be understood whether a meteorological drought condition prevails over a region or not. (The analyses have to be done for all national weather stations throughout longer time periods where data are available). As this analysis is solely dependent upon rainfall the drought that may be confirmed is meteorological drought. Indications of severe meteorological drought can then be disseminated in different regions of a country.
- A comparative assessment should be done on a smaller scale between SPI and remote sensing to find out whether these two tools are complementary to each other in assessing drought.
- Detailed soil data (see earlier about the methods of soil analysis) have to be used from institutions within a regional context.
- The proposed NDIS will be an effective tool. It includes an indicative methodology for the monitoring of drought, which is carried out under a monitoring protocol.
- One of the main objectives of a drought monitoring protocol should be to establish a reliable early warning system.

A simplified landscape–water balance model, which requires soil, abiotical and biotical parameters, in addition to rainfall and potential evapotranspiration data, should be one of the solutions. This model should be able to be transferred in a nonabstracted way to practical field implementation in the region concerned and which is disturbed by drought appearance. This model should also implement European Space Agency (ESA's) methodology, in order to define the final Environmentally Sensitive Areas Index. The assessment should also lead in the first instance into the observations and objections of adaptation options for drought, climate change. These observations should be implemented in the final result of the assessment: the monitoring protocols.

So water crises and drought appearances afford information from diverse disciplines. The goal should be to reduce ecological, societal, economic, and cultural vulnerability to drought [25]. A more risk-based, proactive policy on water and drought management should be adopted through case studies, proper management and planning as well as new technologies [102]. Up to developing and assessing case studies, new technologies have to be stressed. A proper policy should provide a proactive risk assessment and management on national level. The assessment throughout the landscape approach with the landscape scale and regional level interacting has to be fostered and implemented. A proper water supply and related information basis on technical, planning manners, and education for water-efficient behavior have to be transmitted on local community proactive action level: conserving water at everyone's private home and household level. "Using water wisely" as a slogan could, for example, be used in small, private as well as industrial agricultural production to save water around the home or business [107]:

- Consider converting to low-water landscaping.
- Select the right plants for the right place and choose plants, shrubs, and trees that need minimal water.
- Consider drip irrigation for plants, shrubs, and trees.

- Water the lawn early in the morning or later in the evening and be mindful of when it is windy. The water being used may not be getting to your plants and garden in windy weather.
- Limit the used water to approximately one inch (2.54 cm) per week, including rainfall. For best results, the soil should be moistened to between 4 and 6 in. (10.16–15.24 cm) deep with each watering [107].

At the private, nonindustrial, household level the following living standards, personal behavior, and habits should be communicated and adapted to the grade of water availability inside the home [104]: shorter showers should be taken; avoid allowing water to run when shaving, brushing teeth, or hand washing dishes; the faucet should only be turned on when needing; faucets should not be used at full pressure; ensure there is a full load before running washing machines or dishwashers; convert to water-efficient toilets, faucets, and showerheads [107].

The great importance for a holistic approach in order to reach rural, landscape, and environmental security is shown through the diverse already notified managing options again: also the to be bridged diversified planning levels from national to state, regional, local as well as global level and perceptions are giving an insight to the need of holistic assessment structures next to the strongly needed sectoral water-related assessment. By giving the example of the complex land use competitive on local and regional level throughout a potential resulting water crisis or drought appearance, it is making clear that further assessment, management, participatory communication, and (GIS) mapping or participatory mapping as well as networking and guidance are vastly needed.

Competition for land use is an inevitable process to be acknowledged with an integrative as well as a sectoral development outlook of focusing on urban, agglomerated, rural, and transforming areas. Land use competition is eliciting pressures within agricultural and food securing purposes, forestry, living space and infrastructure, energy supply, and raw materials. These multivariate pressures on land are already showing a mandatory necessity in sustainable land use [69]. Sustainable urban and landscape planning or management with including landscape values as well as landscape functions in general are securing social, socioeconomic, ecological, and a cultural balance.

There is a greater need in context of drought prevention and landscape water balance for a further landscape and regional-scaled assessment, management, participatory communication and mapping as well as networking and guidance on sustainable land use, landscape, and regional planning for bewaring and sustaining landscapes [70,72]. Therefore, it has to be stated again that induced land use and landscape-related aspects are of emerging importance for the development of a sustainable terrestrial space. Therefore, the following sections examine the assessment procedure of drought, land degradation, and desertification processes from a landscape scale. The fact that drought may happen in almost any place and climatic zone, except deserts, should imply resilience analyses from the viewpoint of natural, abiotic as well as biotic landscape assessment as always needing to be done within landscape planning procedures (e.g., with an environmental impact assessment (EIA) or a strategic environmental assessment (SEA)).

8.3.1 Drought and Landscape Formations

Drought needs to be considered as a relative, rather than absolute, condition that occurs in both high and low rainfall areas and in virtually all climatic regimes [103]. Drought also happens in humid as well as arid or desert climates worldwide [102] and diverse types of landscapes are concerned. Water shortages are also appearing in years with normal precipitation [102], which give way to degrading processes in the long run. The natural factors of degradation in arid, semiarid, and wet–dry areas are atmospheric stability, continental climate, topographic position, and cold oceanic drifts [89]. Next to natural factors, human-induced factors are influencing degrading processes as well as drought impacts, which are later described in Section 8.3.2.2.

The land surfaces in the world are divided by geographical, political (state boundary) conditions, within climate zones and regions. One driving climatic force is the water (availability). One of the most critical and potential disturbances is fostered by drought appearance and concerns population distribution, settlement, urbanization, agricultural development [21], other land use purposes, and landscape formations in general.

Civilization, urban development, and agricultural cropping patterns are totally dependent on water availability [2,18,21,35] and so also respond to the natural "face/outcome/appearance/design" of a landscape and its structures and forms. The impacts of drought are enormous and result in economic and environmental impacts as well as personal disasters [103]. So, natural resources in general and water resources in particular are essentials for life. Especially water resources are treated as driving force for the development of the entire human civilizations [2,18,38] as well as for their physical environmental surrounding the landscapes.

The example of the sectoral perception of abiotical environmental media such as soil development and fertility development show dependence on a water supply, quality of surface, and groundwater storage [2,18,38]. The linkage between soil consistency, the freshwater cycle, and landscape formations is also given. Natural, geomorphologic (or ecological), and cultural (or social, ritual, comp. again Figure 8.1) landscapes are disturbed by the impacts of drought (comp. again Figure 8.2). Their social, cultural, economic, and other environmental media inhabiting spheres along with their landscape water households have to be considered in dependence on their more or less natural characteristics [2,18,38].

Today's water crisis is impacting more on developing as well as developed countries [102]: some are now developing national strategies and policies for managing droughts more effectively [103]. These activities might be expected in drought-prone nations like Australia, South Africa, the United States, and India. But it is less expected in countries that are considered to have a surplus of water like Malaysia, China, and many European countries [103].

Emphasis has to be given in the research on drought-prone or arid natural, geomorphologic, and cultural landscapes, which indicate temporary or static arid phenomena. Vulnerable parts throughout predestination could be selected or on the contrary more resilient landscape formations or parts of landscapes are most interesting for proper and precautionary risk management. For example, endorheic lakes like the Aral Sea with their non-outlet systems and their surrounding landscapes, ecosystems, and regions in full arid climates have to be acknowledged as being in need of precautionary risk management against drought, land degradation, and desertification. So the to be protected endorheic water cycle is important for the whole catchments water hydrology and has to be sensitively checked about different sorts of water usages. Another example of, in general, more drought-prone cultural landscape, which indicates temporary or static arid phenomena, is the urban landscape, also called city landscape: urban landscapes as part of a cultural landscape may have their specific dry climates, especially when existing megacities have less fresh-air corridors: the capital city of Lima, which is part of the central and southern coast of Peru, already has a mild desert climate next to the Pacific Ocean that makes it one of the driest capital cities in South America as well as in the world. This is a typical phenomenon of west-coast-related landscapes of a continent to inhabit mild desert climates, which results in less water availability.

The examples of inhabiting static arid phenomena should (with acknowledging UNCCD) lead into the perception of spatially delimiting confidence and responsibility to protect further proceeding of droughts, land degradation, a spreading of desertification areas, regions, and landscapes. In the context of landscapes with less groundwater accessibility, precipitation below 250–80 or even 0 mm as well as water scarcity in general, desertificated and desertificating dry lands are located in the cold, arid, and semiarid climate zones. In hyperarid climate zones dry lands and deserts exist. The desertification processes are giving challenges especially in the outbound of the desert areas in sorts of possible desert extensions. Deserts are characterized as being a waste land, barren and typically uninhabited, and also as devastated or ruined, where an eremic, deserticolous lifestyle is prevalent. The following deserts exist worldwide: Arabian Desert, Great Victoria Desert, Libyan Desert, Mojave Desert, Nubian Desert, Nullarbor Plain, Sahara Desert, Scetic Desert, Sonoran Desert, Strzelecki Desert, Syrian Desert, and the Wilderness of Zin [89]. Next to the hyperarid climate zone the with an existing humidity grade characterised semiarid and arid climates are the most important to acknowledge: within these climate zones the spatial distributions of deserts, wilderness, or wastelands have to be in specific assessed and specified for achieving the goal of UNCCD [84]. Landscape and ecosystem monitoring should be carried out in already transformed desert areas. Landscape formations are one of the assessment strategies for combating drought, land degradation, and desertification.

8.3.2 Significance of Different Drivers of Drought and Desertification

Greater water crises than ever have to be faced today worldwide. In humid as well as arid climates, water shortages even in times of normal precipitation are becoming prevalent in developing as well as developed nations [102]. Also droughts of lesser magnitude are resulting in greater impacts [102]. With the existing climate change scenario [83,84] almost half of the world's population will be living in areas of high water stress by 2030, including between 75 and 250 million people in Africa [83,84]. Therefore assessing the significance of different existing drivers of drought and desertification is most important.

As drought relates to drivers of considerable and prolonged lack of rainfall over a wide area, it significantly affects agriculture, domestic water supply, and water-dependent economic activities, even leading to famine [2,18]. Scientifically, drought and its main drivers are defined as the nonavailability of rainfall, which leads to a decreased base flow and a surface flow of water bodies and a depletion of soil moisture [56]. Being a temporary and recurring meteorological event, drought originates from the lack of precipitation over an extended period of time [2,18,55]. The extreme climatic event is often described as a natural hazard. The drivers of drought by themselves do not trigger an emergency, although a long-lasting drought becomes an emergency due to its severe impact on agriculture and the lives of the drought victims [2,18].

Especially for rural areas and their main drivers, pressures and impacts of drought, more specific research investigations have to be done. Also regional sustainable combined social, cultural, ecological and economic drivers, impacts and investigations in sustainable land use management have to be fostered [21]: dry land farming is one example of one of the main rural land use practices in dry regions and landscapes that has evolved as a set of techniques and management practices used by farmers to adapt continually to the presence or lack of moisture in a given crop cycle. The aim behind dry land farming in marginal regions and landscapes is to support the farmer to be financially able to survive occasional crop failures, perhaps for several years in succession.

The main drivers of drought in the context of landscapes and rural areas are observed in the following sections, such as climate change and its role as a driver for eliciting or accelerating drought as well as land use systems, which in a nonsustainable treatment is able to intensify drought [21]. Other multifarious drivers have to be observed in depth as cumulative and synergistic impacts on drought appearance within the frameworks of programs and projects. In a situation of precipitation reduction governments are already eager to act [99] in scientific, technological, or managerial ways against the complexity of drought and to find solutions against its diversified direct or indirect drivers, pressures or impacts of drought. But this eagerness usually wanes when precipitation returns to normal [99]. This means, that not only a crisis management can be a solution for combating drought, but a more continuing, stable and preventive risk and drought management should arise.

8.3.2.1 Climate Change as a Driver of Drought and Desertification

Coping with climate change and its impact on drought and desertification is one of the most important challenges today facing spatial, environmental, regional, and landscape planners, natural and water resource scientists and engineers, stakeholders, and private individuals. Climate change has to be distinguished into abrupt and gradual constellations. Abrupt climate change, with its hazards and disasters, and gradual climate change need the commitment of extended field research at the landscape scale. Especially for projecting the sorts of sustainable landscape planning and long-lasting measurements and solutions needed, gradual climate change is of greatest interest. In its classical definition gradual climate change could be termed following Arnell et al. [6] (citing IPCC [32]) as a "change occurring at historically very high rates, but within the range projected by the Intergovernmental Panel on Climate Change (IPCC), i.e., an increase of 1.5–5.8°C in global average temperature over the 1961–1990 mean by 2100 [32]". Within the definition that "climate change refers to any change in climate over time, whether due to natural variability or as a result of human activity [105]," the relevance for our twenty-first century world and its more or less sustainable future development can be solidified by noting the broad range of scientific fields dealing with the climate and atmospheric sciences [71,73]. On the one hand, the relevance behind the term of climate change and its clearly conceptions and dependencies to natural and cultural systems can and should be approved [70,72] in any region. On the other hand, the relevance of assessing at a landscape scale and approach becomes clearer by acknowledging that global climate change is due to human-induced emissions of greenhouse gasses and that local climate change is due to urbanization and land use changes [43]. As described in the following section, a landscape approached assessment perspective and planning scale is one of the options for counteracting drought and desertification better. Petrosillo et al. ([52], pp. 7–8) have lain down the scientific verification for the importance of landscape ecology in general to stabilize environmental security.

The definition for understanding the approach behind landscapes, specifically of cultural landscapes within the climate change background, has to be mentioned. Following Carl Sauer ([77], p. 46), the dependencies and significance of climate change for landscapes become more obvious: "the cultural landscape is fashioned out of the natural landscape by a culture group. Culture is the agent, the natural area is the medium, the cultural landscape is the result."

Multidimensional scientific specifications, variability, high instability factors, and the complex cause-and-effect relations in adapting to climate change for saving "mother earth," her soil, water, and other environmental media, alongside the evolved landscapes and ecosystems, have to be acknowledged [71,73]. The selection of the most frequent interrelations, spatial dependences, and planning objectives is summarized in Figure 8.1 for abstracting and simplifying some of the most important specifications for planning instances in different sorts of climate change [71,73]: in this figure, a whole theoretical framework for spatial, environmental, and landscape planning in times of climate change is represented. The main scopes, which are interesting for environmental sciences and climate change, are depicted. Included are the climate science–related topic of climate dynamics and variability together with climatologically and atmospheric environmentally related objectives. The most important atmospheric and climate science fields for spatial, environmental, and landscape planning are the ones related to the multifarious micro-, meso-, and macro-climatic processes influencing our the earth's life cycle [71,73].

Extreme events as well as continual steady (gradual) change generate unsecured micro-, meso-, and macro climatic qualities and therefore unstable development conditions for landscapes within the greater processes of climate change and global warming effects (comp. Figure 8.3). Climate change, its extreme events, or continual steady changes in micro-, meso-, and macro-climatic changes are the predominant drivers alongside technologically released changes in the water cycle and water stress [71,73]. Those drivers connote generating unstable development conditions for landscapes and affect our physical, social, ecological, economic, and cultural environment. High temperature and a lower precipitation rate influence these climate dynamics and variability and the water availability within landscapes in the long run [70,72,73] and its inhabiting watersheds (Figure 8.3).

Next to the influenced environmental–sociological movements, civilizatory or in general cultural processes, agricultural crop production, food security, and the natural environment are affected by water cycle changes. Less water availability and water cycle changes also affect the countryside biodiversity and ecosystems, rural land use and landscapes, urban landscapes, and life quality throughout defect landscape functions or changed landscape conditions [71].

Special attention has to be paid to decrease the deficit of instruments that are able to deal with these high instability factors and the complex cause-and-effect relations in adapting to climate change [75]. With these instruments, pressures, dynamics, and impacts can be transferred into sustainable planning, processes, measurements, and mission statements [71,73]. To be included in these focal points are the best possible precautionary, preventive, protective, corrective, collaborative, cooperative as well as legal measures [1] and actions [91,92] for combating climate change.

Newly to be derived political action plans and mission statements, synergies or conflicts of mitigation and adaptation can be dealt with and integrated in the areas of the demand of mitigation thus as the energy-saving demand, energy supply, and adaptation by using climate change strategies [12], reinvented or new planning systems and instruments (comp. Figure 8.3) [73]. As Warren and Khogali [99]

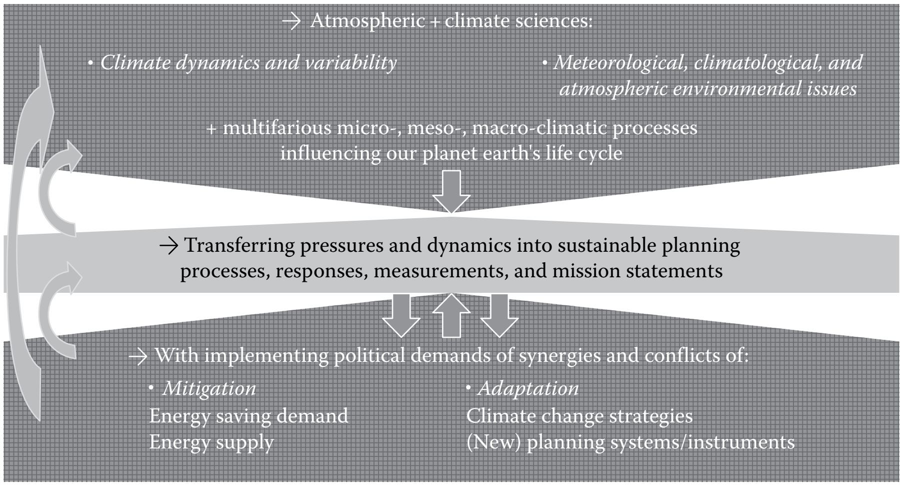

FIGURE 8.3 Planning objectives for climate change. (From Reinstädtler, S., Sustaining landscapes—Landscape units for climate adaptive regional planning, in *Conference Presentation and Proceeding of Abstracts of the International World Heritage Studies* (*WHS*)*—Alumni—Conference, World Heritage and Sustainable Development*, June 16–19, 2011, IAWHP, Cottbus, Germany, Online publication: http://www.iawhp.com/wp-content/uploads/2012/01/IAWHP2011_Book-Abtracts.pdf, 2011, p. 18; Reinstädtler, S., Sustaining landscapes—Landscape units for climate adaptive regional planning, in *Conference Proceeding of the International World Heritage Studies* (*WHS*), *World Heritage and Sustainable Development* June 16–19, published in 2013, 2011, IAWHP, Cottbus, Germany, Online publication: http://www.iawhp.com/wp-content/uploads/2013/05/World-Heritage-and-Sustainable-Development-_-IAWHP-eV_2011.pdf, 2013, pp. 45–65.)

state, drought occurs when the moisture supply is abnormally below average for a period up to 2 years. So next to adapted planning systems to drought and climate change, also strategic, methodological, and instrumental measures of adaptation have to be acknowledged [76] in order to reach long-term planning manners: drought and climate change combined rural landscape and environmental security assessment means also to implement drought adaptation methodologies and tools while assessing three forms of drought adaptation in kinds of optimized land use, especially agriculture in case of food security. An overall adaptation strategy [78] should focus on minimizing the production risk or loss. The adaptation needs to be correlated to climatic impacts and to be manifested by soil, water, and crop management. The options for these adaptation measures can be subdivided into the following three levels [78]:

- Farm level adaptation (or local stakeholders' adaptation)
- System level adaptation
- Planning level adaptation [78].

But most traditional mechanisms at the rural field and community level require modification in recognition of today's problems not being solved with ancient technologies. Adaptation measures within unpredictable risks need to provide for rapid responses, including rescue efforts if necessary, as well as long-term solutions that cut across livelihoods, landscapes, ecosystems, and the social aspects of these communities [88].

8.3.2.2 Land Use Systems Intensifying Drought and Desertification

Almost 50% of the land has been highly degraded by anthropogenic influences [94]. Therefore observing land use systems is becoming more and more important. In the landscapes embedded land use systems and forms such as agriculture, fishery, forestry, trade, industry, and mining next to others are possibly from each other's land use system and its development dependent. At least especially in drought-prone areas there is a greater chance for concurring situations especially in the use of land and water resources. These land use forms might be in a wrong way water managed or land is too intense or sometimes technically wrongly used. So the from soil the depending system of land use is intensifying drought and initiating desertification processes. This means we have to include computer images of desertification as well as descriptions and explanations of drought, land degradation, and desertification in assessment procedures [38]. This was already done in the "Global Atlas of Desertification" [89] by acknowledging a lot of other important features declared in that compendium and first published in 1990: detailed data of the physical and chemical status of soil degradation were used, provided by the Global Assessment of Soil Degradation (GLASOD) [89]. Other important topics were covered and still have to be mentioned in assessing drought, degradation, and desertification—especially important from the viewpoint of the influence of land use systems: desertification and global warming; monitoring on the ground and by remote sensing; vegetation and degradation; local action; cultural factors; financial factors; land reclamations; the political economy and desertification; and desertification and refugees [89].

Drought is—as perceived from human-centric point—next to land degradation, desertification, and those important connected development chains (comp. Figure 8.2) primarily considered as being an agricultural phenomenon. It refers to conditions, where plants are responsive to certain levels of moisture stress, which affects both the vegetable growth and yield of crops [39,40]. Drought appears if the soil is insufficient to meet the optimum need of a particular type of crop for supplying moisture [39,40].

Drought appearance may lead into degradation or desertification (comp. Figure 8.2). The influencing, predominated factors for degradation and desertification are the most interesting for understanding drought and aridity in correlation to land use systems: human-induced climatic degradation factors in arid, semiarid, and dry wet–dry areas (equal desertification) are next to the already mentioned natural factors of degradation (atmospheric stability, continental climate, topographic position, cold oceanic drifts water erosion, wind erosion, chemical deterioration, physical deterioration [89]. Human-induced degradation factors affecting the land are deforestation, overexploitation of the vegetation, intensive agriculture, overgrazing, and bio-industrial factors [89]. In this context, it is important that the United Nations Organization (UNO) has recognized dry lands as being a globally important topic. It is important to support actively the UNCCD, even if over 196 states and European states have already ratified it.

Studies about desertification are giving the xxx, that diverse negative impacts on land use result in dry lands and arid regions [86]. Arid regions are so far the African surrounding of Lake of Chad bordering Chad, Cameroon, Niger, and Nigeria on the edge of the Sahara Desert [26,82], the surrounding of Lake Aral in Kazakhstan and Uzbekistan [46,51,58,89] as well as the Mediterranean Basin as part of South Europe [89]. These examples guide on the one hand the connectivity between climate (change), water, soil, and possible climate and land use related primary or secondary impacts on all environmental media. On the other hand, it also highlights the importance of environmental standards and that ecological, social, and economic impacts from climate and its change syndromes are geographically unevenly distributed [50]. These examples also enhance the thesis that change of land use affects the local climate by affecting the provision of ecosystem services [68]. It also affects people's well-being through damage to human health [41].

Being economically and therefore also in land use related manner very important, Lake Chad as the first inbefore named example serves as a source of livelihood to as many as 30 million people in Chad, Nigeria, Niger, and Cameroon [26]. Near to the Chad basin, the endorheic Lake Chad also provides water to more than 68 million people living in these four countries [82]. But the size of Lake Chad also varies due to the threats of climate change, population explosion, reduced conservation practices, and other human activities [26] like land use practices in general combined with higher water consumption: the Global Resource Information Database of the United Nations Environment Programme shows that the lake has shrunk by as much as 95% from about 1963 to 1998 [82]. This means that it has shrunk from 25,000 km^2 spatial extent in 1963 to less than 2,000 km^2 extent in 2012 [26]. However, satellite images from 2007 show significant improvement over previous years [82]. So, it can be stated that within this example of the life securing elixir of water has to be not only risk or crisis managed interventions have to be fostered. But for a continuing function of the lake of life, a controlled transboundary water, landscape, and land use management is the option for saving life and life quality. A functioning water cycle and therefore securing a self-perpetuating landscape and ecosystem should be the mission behind.

The second example of a land use–related combined landscape and water cycle changed surrounding is guiding us to the in 1950 fourth greatest lake of the world [86]: the freshwater and also endorheic lake of the Aral Sea in Kazakhstan, Tajikistan, Turkmenistan, and Uzbekistan with a former area of 68,000 km^2 [41,50]. The Aral Sea is fed primarily by snowmelt and precipitation from distant mountains, but it has lost its size since the 1960s because of a large water diversion project [45] and intensive land use, such as for the cultivation of cotton and the necessary water abstraction from the headwaters of Amu Darya and Syr Darya [89]. The resulting two-thirds of the volume and half of the lake top were lost by 1997. The water surface sank 16 m up to 1997, resulting in salination [89].

A declined Aral Sea, to 10% of its original size by 2007, was an ongoing process. It split into the four lakes of the North Aral Sea, the eastern and western basins of the once far larger South Aral Sea, and one smaller lake between these two [51,52]. By 2009, the south-eastern lake had disappeared and the south-western lake had retreated to a thin strip at the extreme west of the former southern sea; in subsequent years, occasional water flows have led to the south-eastern lake sometimes being replenished to a small degree [58]. Satellite images [46] from August 2014 have shown for the first time in modern history a completely dried up eastern basin of the Aral Sea [46], which is now called the Aralkum Desert.

The secondary effects of the unsteady development of water availability, frequent drought, the sinking of the water level of lakes, and water shortage were, by 1997 [89], as follows:

- The extinction of aquatic creatures, with no fishing possible anymore
- The contamination of the circumjacent agrarian land, with no agriculture possible anymore
- The deterioration of the climate because of the decrease of the groundwater level, resulting in an aggravation of human health
- The pollution of water by a higher concentration of pesticides as they are returned within the agricultural sewage into the lake.

So the negative impacts upon the Aral Sea up to 1997, even within these examples of secondary effects, are vast and show the tremendous importance of proper water-combined landscape management. This leads us into the Mediterranean Basin of Southern Europe, which concerns Greece, Italy, southern France, Spain, and Portugal [89]. Here, the reason for desertification is among others the climate, soil conditions, poor land use policy, and the further raising of water consumption by industry, agriculture, tourism, and higher living standards. The consequences in the south European area are floods, erosion, groundwater draw down, and salinization [89].

The primary evaluation indicates that an increased utilization of water and natural resources threatens the future of a sustaining water cycle and all dependent ecological, economic, social, cultural, and agricultural functions and food security [35–37,39,40]. The sustainability of water and natural resources are endangered [10,13]. So, for example, modern engineering technologies could use next to the common technological descriptions guidelines to set up protected natural resources regarding land use dry land farming. Also a careful water use and reuse are some of the on-field suggestions to be implemented next to a proper and in the above named cases transboundary water and landscape management. Within the present drought and environmentally harsh conditions a greater need for these interventions is given. The innovation of modern approaches and drought-smart management plans would be the best practice toward protecting water and natural resources while ensuring management sustainability [10,13,21,27].

8.3.3 Landscape Change Indicating Degrading Rural Human-Environmental Systems and Security

The main objective of this section is to support the goals that frame a fundamental theory that indicates landscape change for maintaining and improving environmental stability against drought as well as combined climate change risks. By 2100, one-third of the land will have changed from its former habit or function [9,53]. Landscape change is directly correlated to a qualitative and quantitative, spatial and structural, change in landscapes and implies considerations and indications of the main pressures and driving forces. Drivers, like enhancing, shifting, and varying land use concerns, globalization pressures and dynamical processes in general together with the influences of current political restrictions or spatial planning procedures are combined with more uncertain parameters of climate change risks [71]. These are some of the impacts—alongside drought, land degradation, and desertification—that primarily influence the modern landscapes of the twenty-first century and that have to be acknowledged by reflection on the challenges of landscape change and the term "cultural landscapes" [71]. Landscape change is also driven by changes in water use, which is dependent on the combined effects of changes in water availability [78], changes in water demand for agriculture, as well as from competing sectors including urban development and industrialization, and changes in water management [78].

As desertification is possible in cold, hyperarid, arid, semiarid, dry subhumid, and humid climates, except for desert climates, it is one of the drivers next to land degradation and drought appearance as a potential player in landscape change. The climatic zones in desert areas were, according to UNEP [89], 8% hyperarid, 10% dry subhumid, 12% arid, 14% cold, 18% semiarid, and 38% humid. The most predestined drought regions that will suffer impacts on land use, landscapes, and ecosystems, resulting in dry lands and arid regions or areas are [89] Australia, the greater Asian zones, the southern slope of Europe, the northern slope of Africa, the middle slope of Africa within the Sahel Desert, South Africa, the western part of North America, and South America, especially including the Andes.

For indicating landscape change, other instruments for drought and water scarcity at different spatial scales and levels can be utilized according to Wilhite [102], but have to be correlated by the sorts of landscape assessment and ways of landscape planning:

- Tools to improve surface water resources management under drought conditions
- New agro-meteorological indices for drought identification
- Remote sensing techniques for drought identification
- Mitigation strategies to prevent or deal with drought impacts
- Methods for monitoring and management of groundwater
- Drought monitoring and forecasting techniques, among others, which Wilhite [102] describes in depth in his research.

Implied in this conceptual frame is the need to deal with indicating landscape change in order to estimate the resilience, sustaining, and changing grade of landscapes [71]. Spatial, landscape based, and integrative land use–related instruments are needed to assess in an indicative way the integrative instrument. This should impart encompassing the challenges, needs, and processes for climate adaptive and integrative landscape and environmental planning. Efficiently climate, environmental, and landscape-related data, information, assessments, mission statements, measurements, and scientific together with political development concepts should be used and transferred for estimating indicative and spatially the resilience grade of a landscape [71].

8.4 Managing Landscape and Rural Security in Times of Water Scarcity

Growing water stress in terms of water scarcity and quality deterioration already demands careful water use, water reuse, and proper planning for integrative water management. The IPCC Fourth Assessment Report in 2007 reported that drought is evident in new regions, such as the subhumid areas of southern Africa [31,88]. The IPCC [28] suggests that there is a 90% probability that these developments will take place and implies that there is a need to put in place effective adaptation measures for dryland communities [31,88] for strengthening landscape and rural security.

By 2020, water use and reuse are expected to increase by 40%; 17% more water will be required for food production to meet the needs of the growing population. By 2025, 1.8 billion people will be living in regions with absolute water scarcity; about two out of three people in the world could be living under water and natural resource stress [84].

Therefore, sustainable use of water and natural resources, including the soil, forest, air, oil, gas, and petroleum mining sectors, could be considered for innovation in the sense of sustainable water management in rural regions within a strategic management approach [39,40]. These types of approaches are probable factors for natural resource management in rural regions for the protection of landscapes and ecosystems as well as agricultural food production [32,36–38]. Managing or safeguarding landscape and rural security in the context of water scarcity and drought means also the securing of human life: the most severe droughts during the last 100 years happened in China in 1928, Bangladesh in 1943, and India in 1942 [88]. There, respectively, 3 million, 1.9 million, and 1.5 million human casualties have to be painfully acknowledged [8]. But a different drought management cycle is required: as Wilhite et al. [103] stated, "panic is the first step in the cycle. Then, rain arrives and with it apathy. Neither citizens nor politicians feel the need to prepare for the next drought. But when it does come, panic returns" [103].

It is important to support research and proactive action and implement best practice planning and management options on drought and water management combined with landscape planning aspects. And proper planning procedures have to be structured as, for example following Wilhite et al. [103], a 10-step drought planning process:

1. Appoint a drought task force or committee;
2. State the purpose and objectives of the drought mitigation plan;
3. Seek stakeholder input and resolve conflicts;
4. Inventory resources and identity groups at risk;
5. Prepare and write the drought mitigation plan;
6. Identify research needs and fill institutional gaps;
7. Integrate science and policy;
8. Publicize the drought mitigation plan, build awareness and consensus;
9. Develop education programs;
10. Evaluate and revise drought mitigation plans [59,103].

In the cases of the rural landscape, food security, and life quality greater challenges will be recorded worldwide [52]. Both developments of migration and population growth will present challenges for prognosis in manner of the exposure of water stress [71]. The world's expanding water scarcity, crises, and drought appearances will need proper management technology for resolving the challenges [99]. Also a combined view of mitigation, adaptation, risk management activities, and climate change will have to be fostered for a more efficient drought management. Climate change mitigation, adaptation, and risk management are key components for an integrated observation of climate risks with other areas of risk management [28,29,49] such as wide-ranging approaches for structured decision-making [29,48,63,64,104]. Drought is next to wrong land use and water management or synergistic drivers also climate-related driven. So especially the iterative risk management as part of a more qualitative processing of risk governance [29,65,72] and uncertainty processed decision-making is of greater interest for bringing forward drought management purposes: "iterative risk management involves an ongoing process of assessment, action, reassessment, and response [33,39] that will continue—in the case of many climate-related decisions—for decades if not longer [93]" [29].

The UNCCD is one of the instruments of management that may be successfully implemented [88]: as the sole institution with a United Nations mandate, it focuses on the manner of drought in dry lands and provides policy guidance and proposals to the United Nations system on measures. This will enable drought-prone and newly affected countries to adapt effectively [88]. Next to the secretariat of the UNCCD, the World Meteorological Organization (WMO) and the Food and Agriculture Organization of the United Nations (FAO) also address national drought policy. Meetings are a tool for achieving discursive, observing, and strategic platforms that have been organized, such as the High-level Meeting on National Drought Policy (HMNDP) in Geneva (Switzerland) held during March 11–15, 2013, by UNCCD, the WMO, the FAO, and other partners [106]. In the HMNDP meeting, practical insight was transferred into useful, science-based actions for addressing key drought measurements and strategies to cope with drought better [103].

A broad range of topics that attempt to answer some of the most pressing questions in combination with drought and water scarcity have not been answered yet [86,102], such as for example how to improve planning tools and make mitigation tools more readily available and adaptable. Another technological challenge to be highlighted is how to widespread an adoption of new water-conserving technologies and how to encourage their use during nondrought periods. Until then seasonal forecasts and early warning systems have to be made more reliable and expressed in ways that meet the needs of end users better. Not to be underestimated is the importance of the onset of drought, which needs to be declared as a drought emergency [107]: an emergency response should be activated by state agencies at the national level, as was done in 2005 [107]. Three main subjects have to be fulfilled in the state of Washington in defining and deciding whether to declare a drought [107]: While distinguishing between a "drought" and a "state drought emergency," the "state drought emergency" declaration has to be fulfilled. Then under state law (Washington) institutions and departments must apply the following two-part test before a drought emergency can be declared:

- An area has to be experiencing, or expected to experience, less than 75% of normal water supplies
- An area must be expected to suffer undue hardships as a result of the dry conditions.

The very important step of implementing help and further information for communities, businesses, and farmers affected by drought could be communicated [107]. Best management practices for dairy producers are for example developed in the state of Washington, which would be initiated in a practical sense by a "declaration of drought emergency" [107]:

- Authorize temporary transfers of water rights—to help redistribute water to more critical uses;
- Permit previously drilled emergency wells to be used;
- Permit new emergency wells to be drilled or allow the use of alternative sources of water;
- Issue temporary water permits to expand capacity on existing wells;
- Purchase and lease water rights [107].

A very important next step for time-saving, proactive work is the responsibility for systematically wide spreading, communication, applying, and therefore quicker benefitting of already successfully applied drought-related policy experiences of some countries or federal states [99]. One benefitting example would be a declaration of drought emergency. Indeed, the challenge is that drought and its management are often not seen as an important part of proactive risk management [103]. The more (national) policies and other decision-makers treat this complex phenomenon as a rare and random event [101], which is treated as crisis and restoration management. A solely crisis-oriented perception with leaving out precautionary measurement is not effective in long-termed preventions. It has not laid out effort for concerned individuals or population groups, economic sectors or regions with its ecosystems, and inhabiting landscapes most at risk [101].

Successful research on the findings of these drought and water scarcity insecurities or solutions on planning and management deficits in rural landscapes needs a regional viewpoint: regional assessment and action with bridging a global adapted and innovating perception of the environmental media values. Behind the environmental media values are standing water amount, availability, and quality as well as the landscape and rural securities assessment with incorporating landscape and regional planning aspects [71]. Water scarcity, crises, and drought need considerable information from diverse disciplines with the goal of reducing ecological, societal, economic, and cultural degradation and vulnerability to drought. Drought management also needs the support of national governments, who adopt drought policies for cooperative and coordinative actions at all levels of administration [103]. The aim of national policies should include increasing capacities for coping with extended periods of water shortage resulting from drought [103]: the sense behind "water security" and the implemented characteristics of risk preparedness against this background should be acknowledged. These should be supported by national policy in the understanding of water security itself as lying at the center of many security areas, for example, environmental, landscape, or rural security, each of which is intricately linked to water [85]. Water security—taken into account for policy action—inhabits complex and interconnected challenges and also highlights and brings forward water's centrality for achieving better security, sustainability, development, and human well-being [85]. Also included should be the approval of national and state organized priorities [107]. So the state's priorities are implemented in combination with its comprehensive emergency management plan in the function of responding to a drought [107]. An institution or department has to lead the role for responding to drought and risk mitigation, from which have to be developed specific drought-contingency programs that focus on [107]

- Maintaining crucial energy supplies;
- Protecting public water supplies;
- Aiding state agriculture;
- Safeguarding stream flows for fish;
- Preparing to fight fires [107].

This means in the long run creating more drought resilient societies and ensuring food security as well as the sustainability of natural resource systems at the household level [20,21,27,103].

Again it has to be stated that improved drought policies as well as planning and management means being risk oriented and implementing preparedness plans and programs that are proactive rather than reactive. Reduced risk rather than response to crisis means being more cost-effective, which may lead to more sustainable resource management and the reduced need for interventions by governments [98,99].

8.4.1 Case Study in the Spree Forest Region: Managing Landscape and Rural Security within Water Availability

A balanced regional development needs global functioning or institutional responsibilities in guiding and networking sustainable processes. Furthermore, landscape and rural security play a key role for regional wealth and in kind of synthesizing resilience for handling water availability and its scarcity and drought impacts. These facts are treated in this section within the case study of German Spree Forest Region, which is lying in the federal state of Brandenburg. Spree Forest Region is located in the greater, strongly industrialized and open cast mining impacted Lusatia Region. The region has the advantageous position of lying 80 km south of the German capital of Berlin and 100 km north of the Saxonian federal state capital of Dresden. In the scheme of the theoretical model in Figure 8.4, the correlation between these regions' development chains of rural development supporting instruments, water availability, and rural and landscape security is visualized. This model shows the necessity of a combined view of economic and natural resources [36–39]. Integrative management demands at the landscape scale and at the regional level are shown. Partially instruments are revealed in this scheme with entering this tremendously important step for securing rural environments' [64] and landscapes' regions. The fact of water availability is correlated with the development of rural landscapes (comp. Figure 8.4). Positive examples of applications in the wider region, in the eastern part of German lying region of Lusatia and specifically in the region of Spree Forest, are supplied within this summary of the case study of Reinstädtler: while describing less the theoretically evolved model, Reinstädtler [70] provides favorable examples of the case study [70], which were already proceeded within the region of Spree Forest and the "Man and Biosphere Reserve Spreewald."

In featuring this case study and stressing new management options, the example might encourage nations to adopt a more risk-based, proactive policy for water and drought management [71,73,102]: the proactive option is to begin managing values for rural and landscape security in Spree Forest or for any other region worldwide within scoping water cycles and therefore to respect the correlations and impacts of water availability to rural landscapes development and security (Figure 8.4).

In the regional management of Spree Forest and in the context of "Man and Biosphere Reserve Spreewald" an innovative ecologically oriented and integrated landscape and water management as well as protection needs to balance conservation, restoration, and development. In a constellation of these integrative aims and acknowledging general, theoretical, holistic approaches in landscape science as well

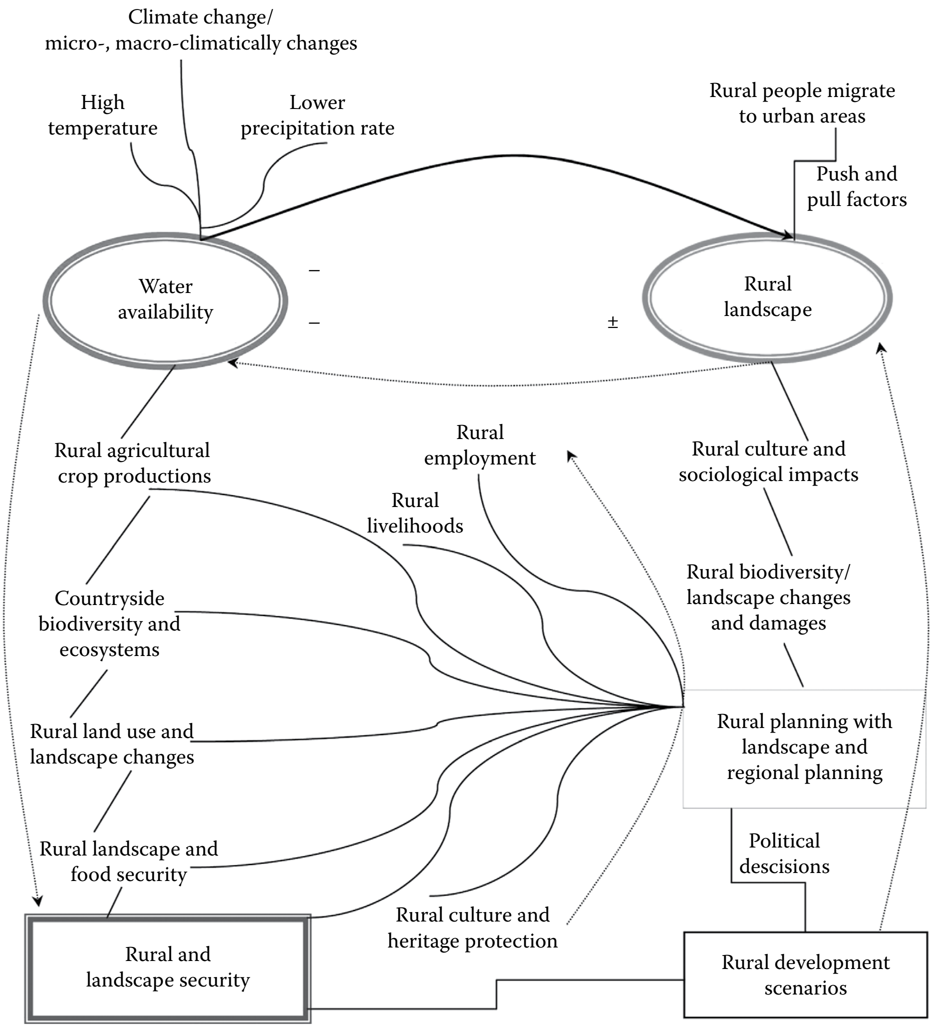

FIGURE 8.4 Water availability and impacts on rural and landscape security from the viewpoint of micro-, meso-, and macro-climatic changes. (After Reinstädtler, S., Sustaining UNESCO MAB reserve spree forest—The right for preserving landscape values in the German Lusatia Region, in *Conference Proceeding of the International World Heritage Studies* (*WHS*), *The Right to* [*World*] *Heritage*, October 23–25, 2014, IAWHP, Cottbus, Germany, 2014; Petrosillo, I. et al., *Use of Landscape Sciences for the Assessment of Environmental Security*, The NATO Science for Peace and Security Series C, Environmental Security, Springer, Dordrecht, the Netherlands, 2008.)

as correlated water balance, we have produced a theoretical model (Figure 8.4) about the correlation of water availability and the impacts on rural and landscape security from the viewpoint of the drivers of climate change or micro- and macro-climatic changes [65,71,73].

As water stress and in-balancing water availability especially in summer times [7,98] are some of the greatest challenges within the management strategies of Man and Biosphere (MAB) Reserve Spree Forests [16,47], it is important to review these challenges. The development strategies named are not completed and are still to be detailed within different regions worldwide. Parts requiring development of strategies for the Spree Forest region are not mentioned here within this model description.

Climate change and global warming effects connote the generating of unstable development conditions for landscapes in the form of extreme events or within a continual steady change in micro–macro climatic qualities.

Climate change and extreme events or a continual steady change in micro-, meso-, and macro-climatic changes are the predominant drivers next to technically released changes in the water cycle and water stress. These drivers also connote the generating of unstable development conditions for landscapes and affect our physical, social, ecological, economic, and cultural environment [71,73]. High temperature and/or a lower precipitation rate influence these climate dynamics and variability and the water availability within landscapes in the long run.

(Rural) landscape development and changing factors are directly dependent on the environmental and landscape water balance. Some of these consequences are listed within this scheme (Figure 8.4). As there will be induced challenges for human life, security, all spatial planning activities, and the intangible as well as tangible face of our landscapes [69,70], this listing is inadequate for even a holistic summary, but they do constitute a beginning. The extent—interesting for the integrative view of landscape, land use, and water-cycle-related change—includes the sociological impacts of rural cultures and heritage: push and pull factors throughout changing systems will apply more pressure for the migration of rural people into urban areas and for less stable conditions for sustaining heritage.

Water stress or less qualitative groundwater (Figure 8.4) might also affect landscapes regarding the changing composition of biodiversity and of the landscape itself, which has already occurred within the MAB Biosphere Reserve Spree Forest [78]. A well-established example of cooperative conservation and development is the charity of cultural landscapes at Spree Forest (Stiftung Kulturlandschaft Spreewald), which was inaugurated in 2007 [16,60]. Landscape change or biodiversity demands are therefore better articulated and protected within a regional and national context. The ecosystems and landscapes embraced biodiversity and its genetical resources of old crop plants that are protected among others throughout places like the herbal garden of Burg [60].

Linkages exist with "education for sustainable development" projects. These are examples of best practice in implementing globally agreed actions and of considerations of local site-specific factors [46], which are implemented in the management strategies of Spree Forest. Also implemented are environmental education, publications, and participatory tools, for example, round tables or information centers, exhibitions, visitor information, guided tours as well as international work camps [15]. An international partnership officially established in 1997 between the Spree Forest reserve and the Palawan Biosphere Reserve of the Philippines [15] rounds off the acquisition of knowledge and the spreading and awareness raising of water stress or landscape changing factors.

More best practice for improving rural areas and rural security are as follows:

- The "charity of cultural landscapes" is an example for inhabiting a well-established cooperative conservation and development [16,60,71] for securing rural values and identity. Landscape changing, environmental media, or biodiversity demands are also better articulated and protected within a regional and national context [73].
- The previously described countryside's biodiversity protection of genetical resources of old crop plants at the better protecting place like the herbal gardens is a good best practice example. So, this botanical equilibrium is one more working measure of rural securing manners.
- There should exist funding programs for rural development, such as the European Agricultural Fund for Rural Development (EAFRD). During funding periods, many projects can be financed by EAFRD by committing public funding and leveraging a high amount of total investment. The projects aim to create and safeguard jobs throughout sustainable oriented production and planning of regionally supported values and ecosystem services. Businesses and private actors implement the projects and partially secure a region's prosperity within the global struggle. In this linkage, it has to be acknowledged that the future development of the Common Agricultural Policy especially in Europe and in EU funding programs need to develop conservation strategies for particularly endangered habitats and species in a changing economic climate and in anticipation of this policy and funding programs [47,73].
- Prioritized procedures of what are in Germany called local action groups, for example, ILE/LEADER projects [46], have the aim of combining the economic and ecological wealth of regions.

- At the local and regional level, "associations" have to be initiated for guiding through these ILE/LEADER or other kinds of projects.
- The associations' tasks are to advocate for the region's economic interests in local production and nationwide marketing and to represent these interests externally with a brand [47,73].
- A sustainable ecological-economic integrating process has to be fostered and not defragmented by demanding reduced qualitative and quantitative aims in the sorts of environmental management strategies for landscape and water resources [73].
- The combination of a created brand and a specific protected area such as World Heritage Sites or MAB biosphere reserves, with their aims of supporting traditional land use, organic food, and agricultural products or regional marketing in general, could be invested in more [61,73].
- In regional management for rural security, an innovative ecologically oriented and integrated landscape and water management as well as protection needs to balance between conservation, restoration, and development. For these integrative aims, we have produced a theoretical model (Figure 8.4) about the correlation of water availability and its impacts on rural and landscape security from the viewpoint of the drivers of climate change or micro- and macro-climatic changes [65,71,73,74].
- This developed schematic model of water availability and impacts on rural and landscape security could be adapted to the assessment in diverse worldwide regions in order to lower the different negative impacts in the correlation of less water availability [71]. An integrative management at the landscape scale and regional level is demanded. Partially instruments are revealed in this tremendously important step for securing rural environments' [64] and landscapes' regions [71]. The fact of water availability is set in correlation to the development of rural landscapes. The development strategies named are not fully complete and are still to be detailed within the different regions worldwide.

Water availability and quality also directly influence rural agricultural crop production and employment creation. In this situation, the MAB Reserve Spreewald has long-lasting experience in discussing and supporting the provision of a better water table for the survival of species and habitats and for ensuring landscape and ecosystem stability as well as for the production of different sorts of agriculture. Optimized conditions according to the MAB National Committee are there to protect environmental and landscape functions in integrating and co-working with diverse stakeholders of the Spree Forest region (Nowak [60], p. 10). So the planning instruments of cooperative planning procedures with a broad public participation and communication throughout active involvement in procedures for conflict mitigation between regional interest groups are well established and ongoing [47].

Especially the countryside's biodiversity landscape and ecosystems, rural land use with especially agricultural crop productions and food security as well as life quality are affected by water cycle changes and less water availability. Also resulting defect landscape functions or changed landscape conditions are forcing the spiral of primary and secondary impacts.

Optimized conditions for rural land use and landscape changes are given in the Spree Forest Region by the "Spree Forest Water Edge Project" [58]. The MAB National Committee indicates this project to be a large-scaled nature protection project as being also from general governmental representative character. Approximately 25 km of water courses have been renatured. The ecological permeability of approximately 50 hydraulic structures and approximately 580 ha of water-ascent areas for protecting Moorish natural landscapes have been developed [61]. So a transregional landscape hydrology plan was included [47].

In the case of the rural landscape, food security, and life quality a greater challenge of insecurity has been recorded worldwide. The coupled developments of migration and population growth will present challenges to the prognosis of exposure to water stress. In the area of the Spree Forest, throughout history, times of water stress and high water rise are known. One of the modern agricultural development paths is the organic farming, which is attracting because of combined environmental friendly agricultural production [60]. Organic farming is occupying one-fourth of the agricultural productive land of the Biosphere Reserve Spree Forest [15]. This is ten times higher than the German average and is one of the examples that illustrates the success story of ecological farming [15].

Rural development scenarios like in specific for climate change prediction purposes were developed within the project of 'Innovationsnetzwerk Klimaanpassung Branderburg Berlin' (INKA BB, engl. translation: 'Innovationnetwork Climate Adaptation Branderburg Berlin'). These scenarios should be fostered for saving culture and heritage protection, rural and landscape as well as water security within the context of environmental security. This scheme shows a greater need for an integrated landscape combined with water management so that the prosperity of the region in terms of natural resources like landscapes and water as well as groundwater may last for many generations to come.

8.4.2 Detection of Regional and Climate Adapted Drought and Integrated Water Management

Frequent drought events, such as in different Mediterranean regions or in Africa and South Asia, show the importance of the UNCCD. The more important UNCCD gets, the more it becomes clear that within such a phenomenon as drought a general insufficiency exists of current strategies for mitigating negative impacts on different water sectors [76]:

- The lack of timely drought monitoring systems;
- The difficulty in transferring advanced methodologies for the assessment of drought risk to the institutions responsible for water resources management;
- The complexity in defining simple and objective criteria to be selected and implemented [74].

The role of the UNCCD becomes even clearer as one of the four main important results of the Rio Summit (three conventions) [73]. The UNCDD was stated to be a unique instrument that has brought attention to land degradation, including influences of drought impacts on land "in some of the most vulnerable ecosystems and affected populations in the world" [88].

The responsibility of the UNCCD for advising UNFCCC parties on related gaps in the current and new agreement [88] vastly helps in creating an integrated network on drought management. Next to these responsibilities, benefits from the largest membership of the three Rio Conventions help to achieve sustainable development and poverty reduction [88]. But in the types of climate change adaptation, recent reviews have indicated that there are many cases with strategies and plans having been developed, but not yet implemented. In the Fifth Assessment Report, "Working Group II: Impacts, Adaptation and Vulnerability," some common barriers are identified from the research literature, including institutional barriers, unclear technical and policy guidance, and weak coordination among the various interests in management and governance [29]. Against the scientific backdrop there still remains uncertainty about the sort of best practice implementation for adaptation measurements [29]. Later on implementation costs might be a barrier, but will it be a significant one? Ideas of strengthening response capacity or resilience have to be transferred to practical advices and measurements [29]. Also several more important targets were discussed within the fifth assessment report of Intergovernmental Panel on Climate Change (IPCC):

- The importance of a direct linkage with sustainable development plans;
- The primary importance of more research on planning processes;
- The focus on the study of adaptation goals themselves;
- The trade-offs between goals;
- The comparative assessment of effectiveness of adaptation strategies within future scenarios of climate change [29].

Another concern could be more about barriers in communication with local stakeholders, including practitioners, knowledge holders, and decision-makers. Participatory processes have to be strengthened and in this way communication and cooperation processes in moderating conflicts have importance like research gaps themselves. Part of the solution is a collaborative research approach with stakeholders and the better enabling of science-based decision-making on climate change adaptation.

In direct correlation to drought management itself some projects like the EU projects Sedemed and Sedemed II (Programme Interreg IIIB MEDOCC) [76] or the 1991 MEDALUS Project (Mediterranean Desertification and Land Use Project) [89] present some main outcomes:

- Appropriate mitigation measures;
- The definition of an integrated network for real-time monitoring of drought;
- The development of common methodologies for drought analysis and forecasting;
- The main limits to an efficient drought management policy;
- Management options for drought with a specific focus on mitigation strategies for the Mediterranean countries [74].

Next to mitigation strategies for drought prone areas, the procedure of combined climate change adaptation and implementing adaptation development plans within this drought management is also very important for reducing drought effects. Only a combined view gives solutions. Within these earlier suggested adjustments of (adaptation) planning and management with special emphasis on landscape planning procedures, the main action field and planning instance are one of preventive (anticipatory, proactive) and corrective, protective adaptations [92,105]. But what stands behind the terminus adaptation? The IPCC [31] defines adaptation as the "adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities." According to Wilson, it is about an "adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities. Various types of adaptation can be distinguished, including anticipatory, autonomous and planned adaptation" [102]. The different sorts of adaptation can be described as follows [71,73]: While anticipatory adaptation takes place before the impacts of climate change are observed, autonomous adaptation "does not constitute a conscious response to climatic stimuli but is triggered by ecological changes in natural systems and by market or welfare changes in human systems" [102]. It is also called spontaneous adaptation. Planned adaptation is the result of "a deliberate policy decision, based on an awareness that conditions have changed or are about to change and that action is required to return to, maintain, or achieve a desired state" [102]. To differentiate between the adaptation forms makes a more qualified detection or management possible. Other forms of approaches for climate adaptation will be discussed later in the text.

First, the combined view for implementing drought management and adapting to climate change has to be discussed. We acknowledge six pillars for drought management in combination with climate change adaptation and implementing adaptation development plans:

1. The application possibilities of adaptation development plans (ADPs) in planning processes, their principles, and the diversified formal as well as informal planning procedures have to be acknowledged while implementing adaptation development plans. Also from state to state different organizational procedures and structures on governmental site should be compromised.
2. For making the implementation of ADPs easier, local level activities are most important. For bringing forward the downscaling necessity of global to the regional and local adaptive capacities and aims to climate change, assessment, measurements, development missions, and monitoring processes have to be included. This local level supports a successful implementation of adaptation plans in sorts of plans, specific development maps, local management plans, agendas, "road maps," or local administrative declarations.

3. For bridging global as well as local needs and for a successful implementation of climate change development planning a transferring agent is needed, which is able to compensate for the different detail grades and scales to be worked on. As already confirmed [70,72,95], the regional level is stated as being the optimized level for implementing sustainable processes. Climate adaptation (and also mitigation) is one condition of sustainable processing for drought prevention. Another optimizing requirement is the regional leveled case study observation in order to implement regional implementation measures for climate adaptation [70,72]. On regional planning level, down- and upscaling is again best possible by fulfilling the very important countercurrent principle in planning proceeding. Also transferable, transparent datasets (dependent on methodologies) can be obtained and further information can be better used within this regional planning [70,72].
4. The methodologies, different tools, and instruments as well as planning procedures and principles have to be adapted to climate change and simplified for proper implementation on (different worldwide) national and environmental, spatial, landscape, and regional planning structures. The different worldwide planning structures at the national level and "adapting" also within these national systems gives the need for smart and simplified implementation of existing and only "CCA-double adapted" instruments. The sorts of insecurity factors in climate change adaptation (CCA) are less advantaged toward the invention of new tools and instruments, but to screen better the existing tools for new CCA—as "being part of the tool." So, for example, Environmental Impact Assessment (EIA) should be proven to implement parts of the "insecurity CCA needed measurements." But within this procedure the legal instances and structural planning background at the national level have to be proven. The Strategic Environmental Assessment (SEA) might be more efficient for CCA, which is already implemented at the plan, policy, and program level in sorts of the precautionary principle in advance unlike EIA implemented later on project level (which is also important). In case of CCA, other possible planning instruments to be used are hazard, risk, and vulnerability assessments, climate check (including mitigation and adaptation, a combined view, and assessment, which are very important), climate proof among a variety of others already mentioned [70,72]. With all instruments and tools, the need of attention has to be checked in their implementation needs and possibilities within formal (and informal) planning structures at each national level. Because planning procedures and traditions cannot be neglected, but having to be proven in their efficiency.
5. CCA methodologies should be applied at the landscape scale. This also means to implement in the assessment and evaluation a holistic and sustainable planning manner. It is obligatory to observe CCA possibilities for all pending pillars of sustainability, and the combination of each, which means integrating the ecological, economic, social, and cultural part within the needs of CCA measurement. The landscape scale is the optimized level for implementing all these parts perfectly at the regional level using the tool of the landscape units (including land use methods) [71,73].
6. Next to the formal aspects already mentioned in point 3, the informal planning aspects are required for a successful implementation of CCA-development plans. Within these informal planning processes, one outstanding planning instrument of participatory processes would be fostered to involve all people concerned and stakeholders at the regional level and also networking and data transference including open-source experience exchanges and platforms from the international to the local level. The fragile subject of spare time framing in adaptation and mitigation for climate change could be met with these informal planning methods in an optimized way. In combination with CCA-development plans, comprehensive monitoring, early warning and information systems, impact assessment procedures, risk management measures, drought preparedness plans, and emergency response programs have to be included in planning and measurement as well as for achieving drought mitigation and CCA [103]. Even strategic response options should be developed and communicated at the national level. Those nations that have not yet adopted nationally coordinated drought policies for providing a framework of proactive, risk-based management and therefore are able to deal with drought events will continue to exist

in a reactive, crisis management mode. Countries without an existing proactive system often illustrate a broader lack of institutional flexibility and preparedness and thus higher vulnerability [30,100]. In this sense, the possibility of funding has to be acknowledged: adaptation measures impose financial obligations on drought-prone countries, over and above what they would normally prepare for if climate change were absent [88]. The Kyoto Protocol's instruments, especially the Adaptation Fund, are well suited to financing the additional costs needed for adaptation measurements and management [88].

8.5 Discussion and Recommendations

It has to be acknowledged that stakeholders' participatory contribution is a most important part of any successful implementation of environmental aims in general and in drought management in particular. So the recommended participatory processes should be implemented in management options for avoiding a one-way road map. A continuing process of an integrative, networking, and participatory drought combined landscape and water-related research is recommended. So in any region worldwide these processes could be further developed and brought forward with also acknowledging and comprising the natural, environmental as well as some of the region's cultural key values. Legally protected areas such as the worldwide existing World Heritage sites or MAB reserves are somehow islands within existing international, national, and federal state laws in different regions worldwide. These are predestined places for pilot projects and monitoring processes with regard to drought, landscape, and water management. So the proposed approach and drought adaptation management framework could be used and implemented properly in developed and developing countries for natural resources, water, soil, environmental and combined landscape management and to ensure the protection of landscapes for community livelihoods as well as for rural security. High-ranged and treasures that are to be validated more in the regions worldwide have to be connected within the existing and suggested frameworks as well as with planning and management mechanisms. These frameworks or planning and management mechanisms behold a regional correspondence and responsibility for an enduring sustainable future of human beings and life on planet earth—the one grounded mother earth.

8.6 Summary and Conclusions

With the aim of reducing drought or land use degradation in general, huge engagement from diverse disciplines is needed: achieving further water resource, soil, landscape, and environmental protection until 2050 and beyond means to activate their specific sectoral protection instruments by official help of diverse institutions and governments and participatory help from persons concerned and stakeholders. As the climate scientist Benjamin Cook in an interview for the actual published climate study [11] stated: "We know from basic physics that warmer temperatures will help to dry things out. Even if precipitation changes in the future are uncertain, there are good reasons to be concerned about water resources." Within the curriculum of UN-Water [85] the meaning of achieving water security is similar, as multiple priority development areas are under consideration, such as conflict and fragility; environmental sustainability; growth and employment; health, hunger, food, and nutrition; inequities; energy; and of course water [85]. Further on the statement stresses the necessity of proper water management for security purposes: "It is safe to state that investment in water security is a long-term pay-off for human development and economic growth, with immediate visible short-term gains" [85].

To secure the world's rural (and urban) landscapes and their inhabited rural and water resource security means in the same row to preserve the agents of an enduring sustainable future of human beings: the agents of their cultural and natural environments, the aesthetics of landscapes themselves, their greater ecosystems, and life in honorable acknowledgment of approved and therefore balancing water availability as well as quality. So, to say in Kofi Annan's words, "I urge governments and communities everywhere to focus on the challenges of life on the desert margins so the people who live there can look forward to a future of peace, health and social progress" [4]. How water availability and drought can be linked with a changing climate and correlated to these changes with changing landscape and rural security strengthens the appeal and sits alongside drought management as one of the major findings in this study.

Summarizing the situation for drought management in terms of constellations of landscape and water resources it can be stated that, within the understanding and development of a sustainable landscape and water management, one key step could have been already done within a successful procedure and methodology of drought management: a combined assessment through protection and monitoring of the landscape and water resources. Therefore, the management process of assessing, protecting, and monitoring landscape and water resources implements large numbers of internationally related organizations, governmental institutions, private persons, business stakeholders as well as policies and law in general. So that these participants can be involved in management processes they have to cooperate, communicate, network, and create synergies as well as bring their knowledge into commitments, consultations and political processes, declarations, and action plans at an inter-sectoral and holistic level. The management mission should not only stand for power, capacity building, and sectoral or static understanding. Management in general means to combine different aspects and planning levels of actions, to cooperate between very diversified stakeholders, to moderate between conflicting different interests, and last but not least to compromise at all stages of management and in the participatory processes. We would like to express the utmost importance of cooperation within participatory processes. Later international policy dialogues will have to be supported so as to influence global drought combined water and landscape treatment, policy and law with regard to sustainable drought, and landscape and water management. Specifically, the national and international landscape and water treatment, laws, and policies are still inadequate to meet the challenges evolving from the global phenomenon of climate change as a main risk to fresh water resources. Adapting to the additional consequences of climate change–induced impacts on especially water resources are inevitable [17], but flexible planning instrumentations have to be developed or rearranged [71,73,75]. Many strategical works exist for CCA worldwide. But only rare nations implemented few adequate measures, which are able to fit to the impacts on climate change [17]. In combination of CCA and the protection of the fresh water cycle and against drought appearance there also exists a huge engagement. But the grade of implementation status should be strongly supported through environmental monitoring.

Conclusions and recommendations for the different regionally related aspects are cultural landscapes with traditional land use methods, including wetland natural resources as well as the ecosystems, are degrading due to anthropogenic influences and natural calamities [39]. In addition to Spree Forest, other cultural landscapes or mountainous regions in diversified regions of the world, such as in Bangladesh, in the Sundarbans region, are facing similar challenges, which have to be communicated for any proper kind of management within networking. In most cases, the drought factors and water of the hydrological cycle in the landscapes and their wetland or other habitat areas are losing balance [34]. A total of 750,000 km^2 of wetlands have been registered worldwide within the evaluations of the Convention on Wetlands of International Importance. It was estimated that 2000 specific wetlands worldwide and also a major portion of other world wetlands are playing an important role to protect the rural landscapes and ensuring rural security through different ecosystem services [52]. In this correlation, we strongly recommend the need for assessing Antarctica or even permafrost areas as a landscape and of importance for the hydrological cycle and drought management in general.

The main scope of interest for drought management within securing landscape and water values in this sense is scientifically integrated and simplifying approaches that are able to confront the most diversified demands at the regional level and to influence as one whole the earth's life cycle [71,73]. Besides drought combined with landscape and water protection, for any region in the world the maintenance and development of areas in accordance with ecologically compatible and traditional land use for reaching the standard of cultural landscape is important. Nevertheless, innovative aspects should be combined to confront the globalizing (financial) pressures for regions to become prosperous. These regions, which include the natural and cultural parts of landscapes, and which are drought endangered, should represent model regions for integrative and innovative approaches, including workplaces in agriculture, commerce, and tourism, for safeguarding or creating regional wealth without disturbing environmental media through negative impacting. The challenge always stands between the lines as in some regions in long-term evaluation can be found between the regional inter-linkages of different interests and conflicts especially in the constellation of land uses. For proper drought management, the water quantity (high rise, scarcity, intermediate level) and quality (different emissions are possible) in the surface as well as groundwater levels have to be approved in an integrated water and combined drought, water, and landscape management strategy. The necessary landscape approach and assessment methodologies for a qualitative-solution-oriented research and implementation has already been applied in one of our diploma theses [69]. It is possible to easily apply within an innovative $CA(LU)^2$-Landscape Meta-Model (including the already applied measuring or monitoring systems of any specific region) for the purposes in any worldwide regions. In this way, the comparative aspect throughout this model between different assessed regions is another conclusion and recommendation. Throughout the Landscape-Meta-Model, stable data and comparable information and datasets can be created for increasing fundamental important networking and experiences exchange so as to save time, money, and other capacities and cultural as well as natural resources.

Water availability (and water quality in similar circumstances) was affirmed in Figure 8.4 to stand in direct correlation to landscape values and functions in a region. A greater responsibility stands behind the very necessary development of short-term, intermediate-term, and long-term planning. Also the technical measurements and management options in sorts of discharge intrusions next to the fact of possibly evolving drought phenomenon and following contamination of water bodies have to be connected to planning needs. The long-term protection of the (cultural) landscapes in which live flora, fauna, and human beings therefore is in danger and has to be dealt with in a prioritized way.

So management systems, especially the regulation of drought and its hydrological regime, have to be innovated and adapted to the impacts of environmental pressures such as intensive land use, transforming landscapes, contaminations, and climate change. The UN is already fostering diversified programs for environment-driven cooperation and networks. Improving the cooperation rate and quality within other international and also national networks would initiate and improve the integrated drought combined landscape and water management.

An integrative character means to foster a step-by-step procedure in management methods, as we cannot solve all of the challenges of drought, land degradation, desertification, or water shortage in one go. "Anyone who can solve the problems of water will be worthy of two Nobel prizes—one for peace and one for science [45]." As we cannot state that all these aims are yet fulfilled, the regional priorities of any worldwide region and its landscape and water values as well as other environmental media should be: the tenor for the prospering regions should be that the functions named in the Seville Strategy as well as in the international guiding principles for different UN environmental programs, declarations should be mainly successfully fulfilled.

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9

Drought Assessment and Management for Heat Waves Monitoring

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Abstract Heat is related to exceptionally high temperatures. Heat generally means thermal discomfort, which activates the thermoregulatory system of the body. Continuous heat increases the discomfort and may cause adverse effects on health, particularly when combined with high levels of humidity or when exacerbated by a person's physical condition. If heat lasts for several days or longer, it is called a heat wave. Moreover, prolonged drought periods also result in reduced humidity, high to very high temperatures, land degradation, possibly desertification, and heat waves or even forest fires. The objective of this chapter is to present a heat waves monitoring methodology that is based on drought assessment and management. The chapter presents a two-stage methodology for monitoring the severity of heat waves over a region. In the first stage, we start with drought quantification through a composite index, followed by drought assessment on a monthly basis, whereby the affected areas are identified. In the second stage, a heat waves frequency analysis is conducted. Finally, a methodology for heat waves monitoring is developed for the affected areas on a daily basis.

9.1 Introduction

Hazards may arise from single-element extremes, such as excessively high temperatures causing physiological heat stress, or from various combinations of elements, such as tropical cyclones with high winds, torrential rain, and storm surge, all posing threats to society, environment, and economy. Potentially hazardous atmospheric phenomena include tropical cyclones, thunderstorms, tornadoes, drought, rain, hail, snow, lightning, fog, winds, temperature extremes, air pollution, as well as climatic change. Estimates of annual global economic losses due to meteorological disasters have shown a significant increase from the 1960s to the early 1990s to nearly $90 billion, and insured losses have also increased to over $50 billion [5].

Hazards producing disasters with economic, environmental, and social impacts have always been attractive to public attention. The public view of climatic hazards has been very sensitive, and there are frequent media reports of events, such as tropical cyclones with significant property damages and losses of life. Moreover, exceptional storms have caused severe damages and killed many thousands of people. Similarly, disastrous floods in Europe have destroyed agricultural lands. Specifically, Hurricane Andrew caused an estimated damage of the order of over $25 billion in Florida and Louisiana in 1992, and Hurricane Mitch in Central America in 1998 [5,10,11,30]. In addition, typhoon Rusa in 1992 was considered the deadliest storm in South Korea. Furthermore, ice and snow storms in the Eastern United States in 1993, 1994, and 1998 resulted in several billions of dollars of loss, as well as the heat wave in the Midwestern and Eastern United States in 1995 and periodic El Nino–related weather events around the world [5,10,11,30].

Lack or deficit of precipitation is the major driving force and feature of drought and constitutes a serious threat for the protection of certain environments, such as the Mediterranean region. Indeed, it is evident that in arid and semiarid regions, the risk of prolonged drought is already there, creating a vicious circle along with climate change and anthropogenic activity. Specifically, drought periods extending in areal coverage and extensive in duration and severity result, among others, in disastrous heat waves and/or extensive forest fires. It is recognized that droughts result in several significant impacts, which can be defined as direct and indirect. Indeed, direct drought impacts include reduced cropland or forest and rangeland productivity, reduced water levels, increased fire hazards, increased livestock and wildlife mortality rates, as well as damage to wildlife and fish habitat. The consequences of these direct impacts are considered as indirect impacts. Furthermore, drought impacts can be classified based on the affected sector, leading to environmental, economic, or social types of impact. In particular, environmental impacts involve the losses that result as a direct consequence of drought; however, they may also involve indirect losses, such as heat waves damage and losses, or wildfire damage to plant and animal species, or even the desertification process. Moreover, several economic impacts affect agriculture and other related sectors. Social impacts refer to public safety, health, quality-of-life issues, water use conflicts, and regional inequities in relief and impacts distribution.

The term "heat wave" refers to unusually high temperatures. Although it can be easily understood as a term, there is confusion among meteorologists about the limits-threshold values of the term. Heat wave is one of the most special kinds of unusual and extreme weather. Heat wave is characterized by higher-than-normal temperatures, low winds, and generally good weather. Although unusual temperatures can occur any time of the year and anywhere, extreme heat waves occur mainly during summers [1]. High temperatures combined with drought episodes constitute very disastrous conditions for the outset and spread of forest fires. Moreover, warm and dry winds favor their expansion and transmission. In subtropical climates, such as the Mediterranean region, most fire incidents occur during midday, when the day temperature is at its maximum level and the relative humidity is at its minimum [72]. It is true that forest fires are one of the most widespread environmental hazards. This risk significantly contributes to climate change and land degradation [18]. The destruction of vegetation by forest fires can have effects on the soil surface and the hydrological cycle through the increase of albedo, surface runoff, reduction of evapotranspiration, increase of erosion, and the presence of floods and desertification. Furthermore, the gases released by the burning of biomass can contribute to the greenhouse effect and cause destruction of the ozone layer.

The objective of this chapter is to develop a heat waves monitoring methodology that results from an assessment of drought impacts. The chapter presents a two-stage methodology for the quantitative monitoring of heat waves intensity or severity over a region on a daily basis. At first, drought assessment and management is considered. Specifically, in the first stage, we start with composite drought quantification by employing a combination of widely used indices of different drought types, followed by drought assessment based on modeling of several drought features. The development of composite drought maps over the examined region leads to quantitative drought severity classification, which constitutes the first stage for the development of heat waves monitoring methodology. In the second stage, the heat waves monitoring methodology is developed, which includes the development of a heat waves quantitative classification scheme, the development of severity–duration–frequency (SDF) relationships, and the development of heat waves early warning systems (HEWS). The chapter is organized as follows: Section 9.2 briefly describes cumulative hazards, which include droughts and heat waves. Section 9.3 presents a composite drought assessment and monitoring methodology, involving composite drought quantification through a combination of indices of different drought types, as well as drought assessment and monitoring. Finally, Section 9.4 presents the second stage of the methodology, which includes the development of a heat waves severity classification scheme, SDF analysis, and the development of HEWS.

9.2 Cumulative Hazards

There is a great variety of climatic hazards with different and significant impacts, which justifies the present concerns of and future challenges for the global climate. Moreover, many atmospheric disasters result from an accumulation of events, where each of them is not usually considered as hazardous. For example, one dry day or even one dry year does not necessarily constitute a drought; however, a succession of abnormally dry years can have disastrous environmental, economic, and social effects. Similarly, hot days are common in many parts of the world, but a succession of many very hot days can lead to disastrous heat waves, especially in areas not normally accustomed to heat waves combined with high humidity.

There has been little evidence of research on climatic hazards before the nineteenth century, with early emphasis mainly on the cataloguing of events, such as tropical cyclones [34], and gradually developing research on tropical cyclones [76] or on drought [22]. Increasingly, the emphasis has shifted to a much greater concern with the nature and alleviation of impacts, involving magnitudes, frequencies, behavior, causes, and impacts of climatic hazards, as well as with studies of perception, planning, preparedness, mitigation, and control (e.g., [64]). Identification of hazardous events is not always easy, although certain criteria are usually employed, which include property damage, economic loss, such as loss of income or a halt in production, or major disruption of social services, communications, and transportation, among others. Moreover, it might be difficult to distinguish between the atmospheric and non-atmospheric factors of climatic hazards. For example, an avalanche depends on the quality and quantity of snow and on the timing of a thaw, but it is unlikely to happen without certain slope characteristics. Furthermore, it is accepted that hot and dry winds may result in fire disasters, but they do not cause them. In addition, increasing losses over time help in focusing on the significance of socioeconomic factors in exacerbating the vulnerability of communities to hazard events. Indeed, more than half of the world's population lives within 60 km of the ocean. Known flood plains and drought-prone regions have experienced development pressures and increased volumes and values of property at risk (e.g., [11]).

A broad distinction can be made between phenomena such as tropical cyclones or severe local storms (and their associated weather extremes, which involve the sudden impact of very large amounts of energy discharged over relatively short periods) and those characteristics that become hazards only if they exceed tolerable magnitudes within or beyond certain limits. It is clear that the latter category may include heat waves, cold spells, flood-producing rains, frosts, fogs, droughts, high winds, snow and ice associated with extra-tropical low-pressure systems, as well as the effects of climate change. Moreover, some climatic hazards result from human activity. Indeed, under the broad umbrella of air pollution, these hazards include impacts to human health, the possible dangers of inadvertent modification of climatic patterns, as well as the effects of acid rain on natural ecosystems. Climatic hazards can be classified into four groups: single-element extremes from common and less common hazards, and compound-element events from primary or secondary hazards [64]. A brief conceptual description of droughts and heat waves follows.

9.2.1 Drought

Drought differs from other environmental hazards in several ways. Among the extreme meteorological events, drought is possibly the most slowly developing and long-lasting event and probably is the least predictable among atmospheric hazards. As already mentioned, drought is a slow-onset environmental hazard, also known as a creeping phenomenon. The driving factor is the accumulated precipitation deficiency, which may happen quickly or may take months before the impacts become apparent. Similarly, due to drought's creeping nature, its effects are also slow to appear, lagging precipitation deficits by weeks or months. Moreover, it is a complicated task to assess the onset and the end time of a drought. It is recognized that because of these, mainly temporal, characteristics, drought cannot be compared with other environmental hazards, such as flood, hailstorm, or frost, which can also contribute significantly to a regional annual loss due to unfavorable natural circumstances. Due to its peculiar character, drought deserves the greatest scientific and operational investigation. The current trend consists of analyzing several well-accepted and widely used drought indices and assessing and comparing their theoretical and practical advantages, limitations, interrelations, potential joint implementation, and numerical effectiveness.

It is difficult to find a generally accepted definition of drought. Drought clearly involves a shortage of water, but realistically, it can be defined only in terms of a particular need [39]. Drought is not just a physical phenomenon, because it results from an interplay between a natural event and demands placed on water supply by human use systems. For a better understanding, drought is classified into several types; however, the relationship between the different types of drought is complex. Specifically, four types of drought are usually recognized: meteorological or climatological, agricultural, hydrological, and socioeconomic. All droughts begin with a deficiency of precipitation in a region over a period of time. These early stages of accumulated departure of precipitation from normal or expected are usually considered as meteorological drought [64]. A continuation of these dry conditions over a longer period of time, sometimes in association with above-normal temperatures, high winds, and low relative humidity, quickly results in impacts on the agricultural and hydrological sectors. Specifically, with the exception of meteorological drought, the other types of drought, such as agricultural and hydrological, emphasize on the human or social aspects of drought, in terms of the interaction between the natural characteristics of meteorological drought and human activities that depend on precipitation, to provide adequate water supplies to meet societal and environmental demands [33]. Needless to say, the relationship between the different drought types is complex. A brief description of the drought types follows.

Meteorological or climatological drought is a region-specific natural event, due to the regional nature of atmospheric phenomena, resulting from multiple causes. It is defined as the degree of dryness specified by deficiencies of precipitation and the dry period duration. Meteorological drought is generally characterized by a precipitation anomaly being lower than average in a region for some period of time and by prolonged and abnormal moisture deficiency.

Agricultural or agrometeorological drought refers to the agricultural impacts resulting from deficiencies in water availability for agricultural use. Indeed, agricultural drought is described in terms of crop failure and exists when soil moisture is depleted so that crop yield is reduced considerably. Specifically, agricultural drought is defined by the availability of soil water to support crop and forage growth, and there is no direct relationship between precipitation and infiltration of precipitation into the soil. In fact, infiltration depends on antecedent moisture conditions, soil type, slope, and precipitation intensity. Soils with low water-holding capacity are typical of drought-prone areas that are more vulnerable to agricultural drought.

Hydrological drought is normally defined by the departure of surface and subsurface water from some average conditions over a long time period resulting from meteorological drought. Hydrological drought is considered to be a period during which the actual water supply, either surface water or groundwater, is less than the minimum water supply necessary for normal operations in a particular region (watershed). Like agricultural drought, there is not a direct relationship between precipitation amounts and the status of surface and subsurface water supplies. There is also significant time lag between departures of precipitation and the appearance of these deficiencies in surface and subsurface components of the hydrological system [63].

Finally, *socioeconomic* drought is defined in terms of loss from an average or expected return and can be measured by both social and economic indicators [43]. Indeed, socioeconomic drought refers to the gap between supply and demand of economic goods brought on by the three other types of drought described earlier, such as water, food, raw materials, transportation, and hydroelectric power, as a result of a weather-related shortfall in water supply. Socioeconomic drought is different from other types of drought since its occurrence depends on spatiotemporal distribution and processes of supply and demand.

As already mentioned, quantification of drought is accomplished through drought indicators, which are variables describing drought features, such as magnitude, duration, severity, periodicity, areal extent, onset, and end time [16]. Primary data for meteorological, agricultural, or hydrological drought indicators are climate variables, such as temperature and precipitation, stream flows, soil moisture, reservoir storage, groundwater levels, snow pack, and vegetation. Data analysis, interpretation, and aggregation lead to drought indicators and/or indices. There are several review studies on the use of drought indicators and indices based on conventional and/or remotely sensed data [27,46,86]. There are questions about the scientific and operational validity of an index, that is, how each indicator is combined and weighted in the index and how an index value is related to the geophysical and statistical characteristics of drought [30]. Nevertheless, drought indices are easy to implement and extensively used in drought quantification and assessment [46].

In evaluating the overall utility of indices, a set of weighted decision criteria is usually assigned to each index that are based on desirable properties of each index, namely, robustness, tractability, transparency, sophistication, expendability, and dimensionality [33]. It is clear that these criteria weights, which reflect the relative importance of the evaluation criteria, are difficult to be precisely justified. The list may be expanded or condensed, but these criteria provide a reasonable framework for the evaluation of drought indices without excessive complication.

Droughts impact both surface and groundwater resources. They can lead to reductions in water supply, diminished water quality, crop failure, reduced power generation, disturbed riparian habitats, suspended or curtailed recreation activities, and a variety of other associated economic and social activities [85]. Long-term impacts on plant and animal life have received relatively little attention, and many questions remain unanswered concerning the role of drought in ecosystems. The impact of drought on human activities is usually described in terms of reduced water supplies and economic losses throughout the community.

Frequent droughts around the world, and interest in their possible links with phenomena such as El Nino, keep the hazard in evidence even for the casual observer. It has been suggested that worldwide disasters triggered by droughts are twice as frequent during year two of ENSO (El Nino Southern Oscillation) warm events as during other years, particularly in southern Africa and Southeast Asia [17]. Several factors may be implicated as potential causes of drought: ENSO, abnormal sea surface temperature patterns in areas other than the equatorial eastern Pacific, soil moisture desiccation, and nonlinear behavior of the climate system [52]. It is tempting also to suggest that climate is changing and that droughts are becoming more frequent and/or more severe. However, there have always been droughts, and records show that events such as those mentioned are within the realm of statistical expectations [38]. Drought is a common feature in many countries, but is often regarded as an unfortunate and irregular abnormality of the environment. It would be more appropriate to consider drought as part of the normal sequence of events. Society must be prepared to cope with the effects of drought at any time. Impacts in the past have been exacerbated by the absence of coping mechanisms, with too little preparation during nondrought periods.

9.2.2 Heat and Heat Waves

Heat is a feeling of discomfort. Heat generally means thermal discomfort, which activates the thermoregulatory system of the body. Continuous heat increases the discomfort and may cause adverse effects on health, particularly when combined with high levels of humidity or when exacerbated by a person's physical condition. If heat lasts for several days or longer, it is called a heat wave. In the mid and high latitudes, heat waves are embedded in the usual course of the summer weather, whereas in the tropics they are endemic. Quantification of heat needs the total energy budget of the human body. This energy budget is influenced by air temperature, humidity, ventilation, radiation, bodily activity, clothing, mass and shape of the body, health state, age, and individual predisposition. In the case of overheating, the body's thermoregulatory system fails to keep the temperature within a tolerable range in the core parts of the body. Indicators in use allow a simplified description of the energy budget of the human body, in addition to capturing effects of heat. These indicators classify the environmental conditions by either recommending the type of feasible bodily activity or requiring the cooling of the human body, both in order to avoid health damage due to overheating.

The climatic conditions show a global distribution of heat stress. In some parts of the tropics, heat stress occurs on more than 300 days/year, and in the midlatitudes, heat stress occurs on about 20–100 days. Indigenous and nonindigenous populations do acclimate to endemic or periodical heat conditions, which helps them to better cope. Heat waves can develop more frequently when, on average, there are more such heat days. In recent years, the number of days with heat stress, and of days with heat waves, has increased in the midlatitudes. The forecast climate change points to further increase of heat stress in many parts of the world. Excessive heat possibly contributes to more illness and mortality than any other direct, weather-related cause, certainly in regions better equipped to cope with the more violent hazards [30]. Most heat-related deaths occur in midlatitude cities, in northern India and China, eastern and Midwestern United States, and Western Europe, with infrequent but extreme heat waves. Subtropical and tropical cities with higher mean summer temperatures seem less vulnerable, partly due to acclimatization of residents and perhaps due to more efficient cooling of houses.

The occurrence of heat waves and their adverse effects are globally widespread. In the last century, about 150 heat waves reaching disaster level were documented [21]. The deadliest heat waves on record globally since 1900 occurred in Europe in 2003 and 2010. Both heat waves were accompanied by an enormous amount of material damage, mostly in forestry and agriculture. Both heat waves were caused by a long-lasting midlatitude airflow pattern, a so-called blocking action. Such weather situations are in general well known, although two factors, namely, high temperature and low precipitation, combine in a particularly unfavorable way. The frequency of heat waves is expected to change in the future [28]. Observations for Central Europe already show that the temperature changes follow a drastic increase of the high (>30°C) and very high temperatures [25], and during the last decades, the number of days with high temperatures has been doubled.

Heat-related deaths, averaging about 1000 per year, appear to be increasing in the United States, exceeding those caused by other hazardous weather conditions [10]. Heat waves may also be associated with increases in the incidence of rioting, violence, and homicide. Heat-related death rates are usually higher in urban areas than in rural areas. This is almost certainly the result of climatic modification and heat retention due to urbanization, the heat island effect, plus the pollution trapping and concentrating effects of stagnant atmospheric conditions of heat waves, adding to those of heat stress. Death rates are also higher among the aged, especially as a result of aggravating effects on preexisting conditions such as heart disease or cancer.

Increased demands for air conditioning and refrigeration can produce overloading of power supply systems during heat waves, leading to power restrictions and breakdowns, which tend to aggravate the heat stress situation. Properly spaced green areas are the most effective and aesthetically pleasing means of controlling urban temperature excess by improving ventilation and circulation and reducing heat storage capacity. Building materials with lower heat conductivity and heat storage properties and water bodies within or close to cities help to keep maximum temperatures down and encourage mixing and ventilation resulting from enhanced temperature differentials. Adequate surveillance systems are needed to alert the public and authorities that potentially dangerous weather is imminent. A promising approach is based on the identification of high-risk air masses historically associated with increased mortality [30]. A similar approach, using a weather type classification scheme developed for North America, has been used in several heat stress warning systems worldwide. It has been incorporated in systems developed for Rome, Shanghai, Toronto, Phoenix, New Orleans, and Cincinnati [61].

9.3 Drought Assessment and Management

Drought identification and quantification is essential for drought assessment and management. Using drought indices is a pragmatic way to assimilate large amounts of data into quantitative information that can be used in applications such as drought forecasting, drought severity classification, preparedness planning, and impact assessment. It is recognized that there is an absence of a precise and universally accepted definition of drought, because there is a wide variety of sectors affected by drought, as well as an increasing water demand for different uses and its diverse spatial and temporal distribution [28]. Definitions of drought are usually region and application or impact specific. Specifically, droughts are regional in extent and each region has specific climatic characteristics. In addition, definitions of drought need to be application specific since drought impacts vary between sectors. Moreover, by considering drought as a hazard, there is a tendency to define and classify droughts into different types. Indeed, definitions of drought can be classified as either conceptual or operational. In particular, conceptual definitions are general and help the public to understand the concept of drought. On the other hand, operational definitions contribute to the identification of the severity and duration of drought and are more useful in drought assessment and planning.

It is accepted that drought indices can be easily implemented and are extensively used in drought quantification, assessment, and monitoring. Indeed, traditional methods of drought assessment and monitoring rely on rainfall data. Although precipitation is the basis of many drought indicators, many other indicators are also significant in the assessment and monitoring of drought severity. Moreover, it is recognized that remote sensing has gradually become an important tool for the detection of the spatial and temporal distribution and characteristics of drought at different scales. In summary, it is best to consider multiple indicators to verify the existence and severity of drought.

Although some drought indices, such as the Standardized Precipitation Index (SPI) and Normalized Difference Vegetation Index (NDVI), are popularly adopted, the variety of drought indices reflects a fundamental lack of universal definition and concepts and different operational requirements. In addition to the variability in the types and applications of droughts (e.g., meteorological vs hydrological), the dissociation of drought indices from drought impacts has prompted calls for aggregate drought indices to cover more aspects and applications.

9.3.1 Drought Quantification: Composite Drought Indices

Drought indices are classified based on the type of impacts they refer to. Moreover, the taxonomy of drought indices can be based on the variables that are used [67] or the use of disciplinary data [50]. Three popular categories are already known, namely, meteorological, agricultural, and hydrological drought indices. However, three more categories have been added: namely, comprehensive, combined, and remotely sensed drought indices [50]. Comprehensive drought indices use a variety of meteorological, agricultural, and hydrological variables to draw a comprehensive picture of drought, such as the Palmer Drought Severity Index (PDSI) [54]. Remotely sensed drought indices use information from remote sensing sensors to map the condition of the land, such as the NDVI [72]. Combined drought indices, which are also termed hybrid or aggregate or composite [79], are derived by incorporating existing drought indicators and indices into a single measure, such as the U.S. Drought Monitor (USDM) [67].

9.3.1.1 Global Composite Drought Indices

During the last decades, a web services–based environment is being developed for integration of regional and continental drought monitors; for computation and display of spatially consistent drought indicators on a global scale, such as in situ SPI, satellite-based indices, and modeled soil moisture; and for drill-down capacity to regional, national, and local drought products. Each continental drought monitor is developed and functions according to the unique conditions of that continent. At the present time, there are several regional/continental drought monitor models that together form the Global Drought Monitor (GDM) and coordinate and exchange information with a Global Drought Information System (GDIS). Specifically, the four major regional/continental models are the North American Drought Monitor (NADM), which consists of the USDM, Canada, and Mexico, the European Drought Observatory (EDO) model, the African Drought Monitor (ADM), and the Australian Drought Monitor model [16]. There is an international need to continue working toward newer and potentially better drought indices that can also account for a changing climate in which there may be a shift in both temperature and precipitation regimes. The USDM system and the EDO model are briefly discussed next.

9.3.1.1.1 U.S. Drought Monitor (USDM)

The USDM [67,82] is a composite drought index. The USDM integrates multiple indices, such as SPI and PDSI, as well as indicators, such as vegetation and hydrological conditions, into a weekly map of drought. This information is later subjected to expert interpretation for refinement. Because of its composite nature, the USDM can respond to the needs of various water users, including water planners and the agriculture industry. The USDM system uses a composite of multiple indicators covering various short- and long-term time frames to develop a ranking methodology for drought analysis, leading to a single index [67]. The USDM is an operational product issued weekly since 1999 and provides a general up-to-date summary of current drought conditions across the lower 48 states, Hawaii, Alaska, and Puerto Rico. The USDM uses a Fujita-like drought classification, as shown in Table 9.1, with four drought categories (D1–D4) and an abnormally dry category (D0) based on percentile rank. The USDM system has also the flexibility to integrate new tools and data and additional information, if available, in order to enhance the level of accuracy. Depending on the data availability and quality for any particular area, it may be possible to utilize many drought indices that are available and determine the most suitable for any particular area or season for drought monitoring and drought early warning systems (DEWS). There are also hybrid types of drought indices where satellite data are merged with surface data, such as the Vegetation Drought Response Index (VegDRI) [4].

The USDM operates in two drought impact assessment schemes, namely, the short-term and the long-term scheme. Specifically, the short-term scheme approximates drought-related impacts that respond to precipitation and, secondarily, to other factors on time scales ranging from a few days to a few months, such as wildfire danger, nonirrigated agriculture, topsoil moisture, range and pasture conditions, and unregulated stream flows. The *short-term* composite drought index consists of 35% Palmer Z-Index; 25% 3-Month Precipitation, 20% 1-Month Precipitation, 13% Climate Prediction Center Soil Moisture Model, and 7% Palmer (Modified) Drought Index. Similarly, the *long-term* scheme approximates drought-related impacts that respond to precipitation on time scales ranging from several months to a few years, such as reservoir stores, irrigated agriculture, groundwater levels, and well water depth. Indeed, the long-term composite drought index consists of 25% Palmer Hydrologic Drought Index, 20% 12-Month Precipitation, 20% 24-Month Precipitation, 15% 6-Month Precipitation, 10% 60-Month Precipitation, and 10% Climate Prediction Center Soil Moisture Model.

TABLE 9.1 Drought Severity Ranking (Fujita Scale)

Percentile Rank	Drought Severity
21–30	D0: Abnormally Dry
11–20	D1: Drought—Moderate
6–10	D2: Drought—Severe
3–5	D3: Drought—Extreme
0–2	D4: Drought—Exceptional

9.3.1.1.2 European Drought Observatory (EDO) Model

As already mentioned, a reduction in the average precipitation is the primary driver of drought. When this precipitation reduction causes a decrease in soil moisture, which in turn does not satisfy the water demand of plants and therefore affects their physiological processes, then agricultural drought begins. Based on this process, a method that combines different drought indices, namely, SPI, soil moisture anomalies, and the Fraction of Absorbed Photosynthetically Active Radiation (fAPAR) anomalies, has been developed in order to identify not only areas affected by agricultural drought, but also areas with the potential to be affected. Specifically, the Standardized Precipitation Index (SPI-*n*) [42] is a statistical indicator comparing the total precipitation received at a particular location during a period of *n* months with the long-term rainfall distribution for the same period of time at that location. It is one of the most common drought indicators that has been selected by the World Meteorological Organization as a key meteorological drought indicator to be produced operationally by meteorological services. Similarly, soil moisture (pF) is one of the important variables in hydrological, climatological, biological, and ecological processes because it plays a crucial role in the interactions between the atmosphere and the land surface. Moreover, the fAPAR represents the fraction of the solar energy that is absorbed by vegetation. It has been proposed as a drought indicator due to its sensitivity to vegetation stress. Indeed, droughts can cause a reduction in the vegetation growth rate, which is affected by changes either in the solar interception of the plant or in the plant's light use efficiency.

The method consists of a classification scheme based on three drought impact levels, corresponding to the different stages of the idealized agricultural drought cause–effect relationship. These levels are named as "Watch," "Warning," and "Alert." Two additional levels, "Partial recovery" and "Recovery," identify the stages of the vegetation recovery process. In general, drought assessment is conducted using individual indices, based on meteorological data or remote sensing images. The development of a composite index by combining and integrating meteorological and remote sensing indicators can help reduce false alarms, for example, in the case of vegetation indices, where a biomass reduction can happen due to causes different from those of a drought-induced water stress.

9.3.1.2 Meteorological, Agricultural, and Hydrological Composite Drought Indices

The selection of an appropriate drought index is based on several criteria and factors [66], such as data availability, cost, suitability for the drought type under study, consistency and practicality, clarity and scientific validity, temporal and spatial sensitivity and variability, as well as specific duration and regional scale, for example, a watershed versus a climatic classification [86]. Moreover, there should be well-defined thresholds and criteria for drought onset and end time, and statistical consistency within drought levels, as well as with other indices. As already mentioned, six criteria are considered for the evaluation of meteorological drought indices, namely, robustness, tractability, transparency, sophistication, extendability, and dimensionality [33,48,58].

9.3.1.2.1 Meteorological Drought Indices

The development and implementation of a drought index heavily depends on data availability [67]. Meteorological drought indices include precipitation-only indices such as Rainfall Anomaly Index (RAI) [73], Bhalme–Mooley Drought Index (BMDI) [3], Drought Severity Index (DSI) [6], National Rainfall Index (NRI) [25], Effective Drought Index (EDI) [8], and Drought Frequency Index (DFI) [26]. For better correlation with drought impacts and better accounting for temporal temperature trends, additional meteorological variables have been considered. These include modifications to SPI [42] to develop the more comprehensive Reconnaissance Drought Index (RDI) [70], which incorporates evapotranspiration, thus resulting in better association with impacts from agricultural and hydrological droughts. Moreover, there is a similar index, namely, Standardized Precipitation Evapotranspiration Index (SPEI) [75], which is sensitive to long-term trends in temperature change. If such trends are absent, SPEI performs similarly to SPI. Keetch–Byram Drought Index (KBDI) [32] considers temperature and has wide application in wildfire monitoring. Palfai Aridity Index (PAI) [53] considers groundwater in addition to the above indices and has mainly been applied to basins. In addition to temperature and evapotranspiration, PDSI [54] also considers stream flow and soil moisture to give a more complete picture of the water balance. PDSI is categorized as a "comprehensive" drought index [50] and remains a popular index. Improvements include self-calibration capacity [82] and modifications to the evapotranspiration estimation methods, replacing the original Thornthwaite method [68] with other formulations.

9.3.1.2.2 Agricultural Drought Indices

Approaches to characterize agricultural drought mainly involve monitoring of soil water balance and the subsequent deficit if a drought occurs. This applies to several nonremote sensing agricultural drought indices: Relative Soil Moisture (RSM) [69]; Crop Moisture Index (CMI) [55], which is similar to PDSI, but models short-term agricultural drought by considering moisture deficit only in the top 5 ft of soil column [8,48]; and Crop Specific Drought Index (CSDI), originally designed for corn and its variant for soybean [45]. Agricultural Drought Index (DT*x*) [41] calculates the daily transpiration deficit (DT) for *x* days. DT*x* uses the CRITeRIA soil moisture balance model [84], with inputs including soil, crop, and weather conditions, in addition to temperature anomalies that affect evapotranspiration. Increased spatial and temporal resolutions were sought in developing Soil Moisture Deficit Index (SMDI) and Evapotranspiration Deficit Index (ETDI) [48]. This approach considers the soil component of the Soil and Water Assessment Tool (SWAT) hydrological model, which has a resolution of 16 km^2, as compared with the 7,000 km^2 and 160,000 km^2 resolution of SPI and PDSI, respectively. Within the top 2 m of the soil component, "soil profile," SMDI characterizes soil moisture deficit at varying depths: top 2 ft (SMDI2), 4 ft (SMDI4), and 6 ft (SMDI6). SMDI2 and ETDI, which considers evapotranspiration deficit, have been recommended for short-term drought conditions monitoring and SMDI6 for long-term monitoring. Remote sensing–based vegetation indices such as NDVI [72], Temperature Vegetation Dryness Index (TVDI) [19], Enhanced Vegetation Index (EVI) [40], Vegetation Drought Response Index (VegDRI) [4], Temperature Condition Index (TCI) [35], and Normalized Difference Water Index (NDWI) [23] are also used to monitor general vegetation state and health [62].

9.3.1.2.3 Hydrological Drought Indices

This group of indices aims at providing a comprehensive characterization of delayed hydrological impacts of drought [22]. Earlier, the advanced Palmer Hydrological Drought Index (PHDI) [54] model considered precipitation, evapotranspiration, runoff, recharge, and soil moisture. The PDSI family of indices lacked the snow accumulation component, which led to the development of Surface Water Supply Index (SWSI) [60], probably the most popular of this group. Later, Reclamation Drought Index (RDI) [81] was developed as an improvement over SWSI by incorporating temperature and hence calculated a variable water demand as input. Remote Sensing Drought Index (RSDI) [65] bases its model on homogeneous drought-stricken regions that comprise several neighboring low-flow gauging stations. RSDI first calculates the deficiency in streamflow compared with historical values and then uses cluster analysis to delineate the drought-stricken regions. Two later indices, namely, Groundwater Resource Index (GRI) [44] and Water Balance Derived Drought Index [74], consider a water balance model. The former focuses on groundwater resources and uses information on geolithological conditions in a distributed water balance model, whereas the latter artificially simulates runoff for ungauged and low-flow watersheds.

9.3.1.2.4 Remote Sensing Potential

New sensors and algorithms have constantly enabled the incorporation of improved remotely sensed information in drought characterization. New sensors have higher spatial resolution, a current shortcoming in drought indices [50]. Novel noise reduction algorithms and other atmospheric correction algorithms improve the thematic accuracy of remote sensing datasets. Remote sensing indices are diverse and new indices are frequently proposed. While NDVI has remained popular [7,56], other indices such as VegDRI, Vegetation Condition Index (VCI) [36], Temperature Condition index (TCI), and Vegetation Health

Index (VHI) [35] are currently operationally used [49,51]. Traditionally used bands include near-infrared (NIR), red, and short-wavelength infrared (SWIR). The land surface temperature (LST) has been used as an additional source along with NDVI to improve drought characterization accuracy [9,37,57,59,77,78]. A comprehensive review of the performance of the large number of remote sensing drought indices for different configurations can be helpful.

9.3.1.2.5 Aggregation of Drought Indices

Nonhybrid indices are mainly useful for particular places and specific objectives or applications and do not provide a comprehensive characterization of drought events. Combining various drought indices has been increasingly discussed as a means to incorporate and more effectively exploit information that is readily available and proven to be useful in field-specific drought indices [29,50,62]. Following the Lincoln Declaration, Sivakumar et al. and WMO [62,83,84] recommended the creation of a new composite hydrological drought index that would cover stream flow, precipitation, reservoir levels, snowpack, and groundwater levels. In general, hybrid drought indices can provide a stronger correlation with actual impacts sustained on the ground. Most hybrid drought indices are comparatively recent, including the USDM [67] and VegDRI [4]. VegDRI combines SPI and PDSI, in addition to two NDVI-based indicators: Percent Average Seasonal Greenness (PASG) and Start of Season Anomaly (SOSA). Moreover, a combination of SPI, SWSI, and PDSI was accomplished to develop the integrated Hydrological Drought Index (HDI) [31].

9.3.1.2.6 Climate Change Effects

The predicted nonstationarity of future climates [28] has instigated research for including future temporal patterns in drought characterization. SPEI [75] accounts for the increase in the duration and magnitude of droughts resultant from higher temperatures. Additional research has been conducted for specific regions, including research for an Australian index [47] and another from the Czech Republic [20].

9.3.2 Drought Features and Assessment

For assessing and monitoring droughts, several drought features are usually detected. Specifically, conventional and/or remote sensing data and methods can be used to delineate the spatial and temporal variability of several drought features in quantitative terms [14–16]. A description of some key features follows. *Severity*: Severity or intensity of drought is defined as escalation of the phenomenon into classes from mild, moderate, severe, and extreme. Severity is usually determined through drought indicators and indices. The regions affected by severe drought evolve gradually, and there is a seasonal and an annual shift of the so-called epicenter, which is the area of maximum severity. *Periodicity*: Periodicity is the recurrence interval of drought. *Duration*: Duration of a drought episode is defined as the time interval from the onset of the drought to the end time, usually in months. Since drought is a complex phenomenon, the assessment of the onset and the end time is a complicated technical subject. *Onset*: Onset of a drought signifies the beginning of a drought episode. The beginning of a drought is assessed through a certain threshold value of indicators or indices. *End time*: End time of a drought episode signifies the termination of drought, based again on threshold values of indicators or indices. It is often difficult to determine the onset and the end time of a drought, and on what criteria these determinations should be made. *Areal extent*: Areal extent of drought is the spatial coverage of the phenomenon as is quantified in classes by indicators or indices. Areal extent varies in time, and remote sensing has contributed significantly in the delineation of this parameter by counting the number of pixels in each class. From a planning perspective, the spatial characteristics of drought may have serious impacts on several sectors of the economy, such as agriculture, energy, transportation, health, recreation, and tourism.

For drought assessment, two remotely sensed drought indices are used, namely, Reconnaissance Drought Index (RDI) [71], which is a meteorological drought index [14], and Vegetation Health Index (VHI) [35], which is an agricultural drought index [15]. The combined use of these two indices for drought assessment gives a composite index that is a data-driven model based on remote sensing data and methods. This means that empirical models can be developed for every region, provided that there are available remote sensing data. The study area for this research work is Thessaly in central Greece, which is a drought-prone agricultural area [14,15].

9.3.2.1 Remotely Sensed Estimation of RDI

The estimation of RDI is based on remote sensing data and techniques. Specifically, the methodology follows several steps, which include prepossessing of satellite data, calculation of air temperature, estimation of potential evapotranspiration with the use of satellite data, rain map extraction, and remotely sensed estimation of RDI. A brief description follows. Estimation of RDI is based on monthly temperature maps, crop coefficient (*Kc*) maps, sunlight maps (*p*), Potential Evapotranspiration (PET) maps based on the Blaney–Criddle method, and rain maps (*P*). In this study, RDI is calculated on a monthly and annual basis. The calculation of the index starts with the estimation of a_k coefficient, given in the following equation:

$$a_k = \frac{\sum_{j=1}^{j=k} P_j}{\sum_{j=1}^{j=k} PET_j} \quad (9.1)$$

where P_j and PET_j are precipitation and potential evapotranspiration, respectively, in the *j*th month of the hydrological year. The hydrological year for the Mediterranean region starts in October; hence, for October, $k = 1$. RDI_n is the Normalized RDI, which is given by

$$RDI_n(k) = \frac{a_k}{\overline{a_k}} - 1 \quad (9.2)$$

The Standardized RDI (RDI_{st}), which is used in this study, is given by

$$RDI_{st}(k) = \frac{y_k - \overline{y_k}}{\hat{\sigma}_k} \quad (9.3)$$

where

y_k is the ln a_k
$\overline{y_k}$ is its arithmetic mean
$\hat{\sigma}_k$ is its standard deviation

The drought categories based on RDI are shown in Table 9.2.

TABLE 9.2 RDI Drought Classification Scheme

Drought Categories	RDI Values
Extremely wet	≥2.00
Very wet	1.50–1.99
Moderately wet	1.00–1.49
Near normal	0.99 to −0.99
Moderately dry	−1.00 to −1.49
Severely dry	−1.50 to −1.99
Extremely dry	≤−2.00

Source: Tsakiris, G. and Vangelis, H., *Eur. Water*, 9(10), 3, 2005.

9.3.2.2 Remotely Sensed Estimation of VHI

The estimation of VHI from remotely sensed data on a monthly basis follows certain steps [15]. At first, preprocessing of satellite images is done, which includes geometric and atmospheric correction of all images. Certain filters are used for smoothing the data, which is an improvement in the procedure, resulting in the improvement of VHI's performance. Then, the computation of the VHI is carried out and monthly VHI images are produced on a pixel basis. Indeed, the computation of VHI on a monthly basis uses satellite data for brightness temperature (BT) and Normalized Difference Vegetation Index (NDVI). VHI is a combination of Vegetation Condition Index (VCI) and Temperature Condition Index (TCI), both derived from NOAA/AVHRR satellite data [35]. VCI is based on NDVI (and is an extension of NDVI) and is expressed in the following equation:

$$VCI = 100 * \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \tag{9.4}$$

where $NDVI$, $NDVI_{max}$, and $NDVI_{min}$ are the smoothed 10-day NDVI, its multiyear maximum, and its multiyear minimum, respectively, for each pixel, in a given area. Similarly, TCI is based on the same concept as VCI and is expressed in the following equation:

$$TCI = 100 * \frac{BT_{max} - BT}{BT_{max} - BT_{min}} \tag{9.5}$$

where BT, BT_{max}, and BT_{min} are the smoothed 10-day radiant temperature, its multiyear maximum, and its multiyear minimum, respectively, for each pixel, in a given area. Vegetation Health Index (VHI) represents overall vegetation health and is used for drought mapping and crop yield assessment. The five classes of VHI that represent agricultural drought, as well as no drought conditions, are illustrated in Table 9.3. Specifically, from Table 9.3, it is evident that drought severity decreases with increasing VHI values. *VHI* is expressed in the following equation:

$$VHI = 0.5 * (VCI) + 0.5 * (TCI) \tag{9.6}$$

VCI and *TCI* vary from zero, for extremely unfavorable conditions, to 100, for optimal conditions. *VCI* and *TCI* characterize the moisture and thermal conditions of vegetation, respectively. Thermal conditions are especially important when moisture shortage is accompanied by high temperature, increasing the severity of agricultural drought and having a direct impact on vegetation health. In many parts of the world, TCI along with VCI has proven to be a useful tool for the detection of agricultural drought [15,35].

TABLE 9.3 VHI Drought Classification Scheme

VHI Values	Vegetation Drought Classes	Drought Class Numbers
≤10	Extreme drought	1
≤20	Severe drought	2
≤30	Moderate drought	3
≤40	Mild drought	4
>40	No drought	5

Source: Kogan, F.N., *Adv. Space Res.*, 15, 91, 1995.

9.3.3 Drought Monitoring

For illustrative purposes, two cases using empirical models and leading to the development of DEWS, one based on RDI [14] and the other based on VHI [15], respectively, are briefly presented. Eventually, the combined use of both indices leads to the development of a composite framework for drought monitoring and assessment.

9.3.3.1 Meteorological DEWS: RDI

By plotting the cumulative monthly areal extent values of the extreme RDI drought class, that is, class 4 [14] with values lower than −2, for all the drought episodes, two figures are produced, namely, Figure 9.1 for droughts of large areal extent and Figure 9.2 for droughts of small areal extent. Furthermore, curve fitting is conducted for each of these figures, resulting in the following polynomials, namely, Equation 9.7

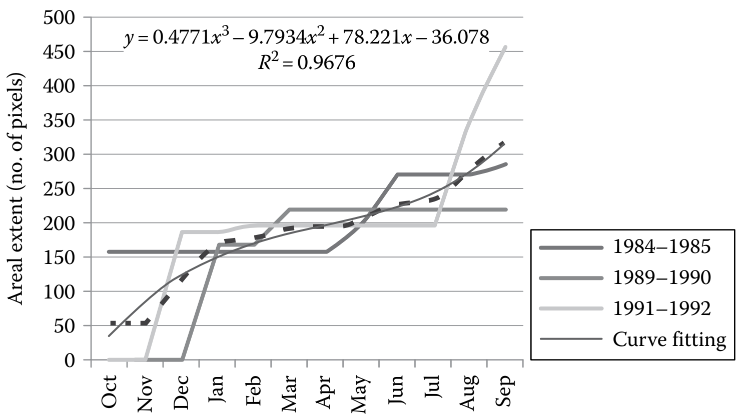

FIGURE 9.1 Cumulative large areal extent (no. of pixels: 8 × 8 km^2) of extreme drought (<−2.0) during drought years based on remotely sensed Reconnaissance Drought Index (RDI). (From Dalezios, N.R. et al., *Nat. Hazards Earth Syst. Sci.*, 12, 3139, 2012.)

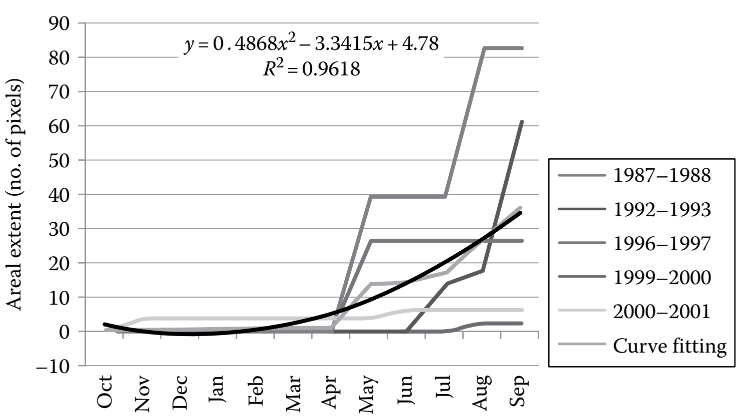

FIGURE 9.2 Cumulative small areal extent (no. of pixels: 8 × 8 km^2) of extreme drought (<−2.0) during drought years based on remotely sensed Reconnaissance Drought Index (RDI). (From Dalezios, N.R. et al., *Nat. Hazards Earth Syst. Sci.*, 12, 3139, 2012.)

for droughts of large areal extent and Equation 9.8 for droughts of small areal extent, both with a high coefficient of determination:

$$y = 0.4771x^3 - 9.7934x^2 + 78.221x - 36.078 \quad (R^2 = 0.9676) \tag{9.7}$$

$$y = 0.4868x^2 - 3.3415x + 4.78 \quad (R^2 = 0.9618) \tag{9.8}$$

It is worth noticing that for droughts of large areal extent (Figure 9.1), drought starts during the first 3 months of the hydrological year, whereas for droughts of small areal extent (Figure 9.2), drought starts in spring (April). This finding signifies the possibility of using the fitted curves for monitoring and early warning drought assessment in a region. This finding justifies the use of the fitted curves of Figures 9.1 and 9.2, along with the corresponding Equations 9.7 and 9.8, for drought prognostic assessment or the development of DEWS.

9.3.3.2 Agricultural DEWS: VHI

The cumulative monthly areal extent curves of the two merged classes, which correspond to the four VHI severity classes of agricultural drought, are presented in Figure 9.3 [15]. Furthermore, curve fitting is conducted for each of these curves, resulting in the following polynomials, namely, Equation 9.9 for high-severity areal extent drought and Equation 9.10 for low-severity areal extent drought, both with a high coefficient of determination:

$$y = 0.0905x^2 + 4.3574x \quad (R^2 = 0.9168) \tag{9.9}$$

$$y = -3.7413x^3 + 34.977x^2 - 6.8352x \quad (R^2 = 0.9998). \tag{9.10}$$

The two curves of Figure 9.3, namely, the cumulative monthly areal extent curve of high-severity classes (Equation 9.9) and the corresponding curve of low-severity classes (Equation 9.10), delineate the range of values that agricultural drought may show every year during the warm season. These findings signify the

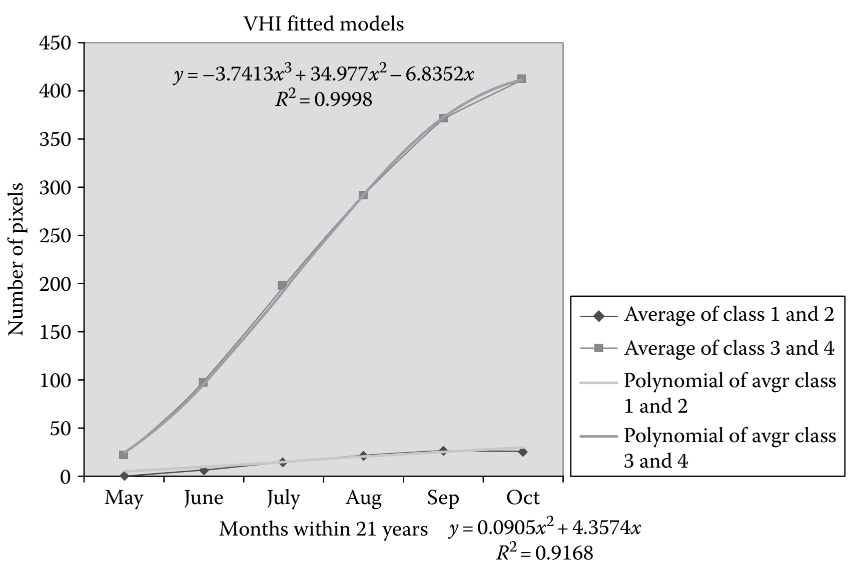

FIGURE 9.3 Fitted models of cumulative areal extent (no. of pixels) of average monthly drought VHI values for the two sums of severity classes. (From Dalezios, N.R. et al., *Nat. Hazards Earth Syst. Sci.*, 14, 2435, 2014.)

possibility of using the fitted curves for monitoring and early warning drought assessment in any region, although the actual VHI values may be different for different regions. Thus, the fitted curves of Figure 9.3, along with the corresponding Equations 9.9 and 9.10, can be used for first-guess drought prognostic and monitoring assessment, leading to the development of DEWS.

9.4 Heat Waves Monitoring Methodology

It can be stated that, in general, droughts and heat waves have shown to be associated with the persistence of ridges or centers of high-pressure systems in the middle atmosphere. Moreover, the corresponding reduced cloud cover results in positive temperature anomalies in the lower atmosphere, which produces the middle-level pressure anomaly and favors subsidence at the high level, thus keeping the atmosphere significantly drier and more stable than normal [16]. Studies in several areas around the world have shown that drought periods are often characterized by a large decrease in the amount of rainfall per day, by an increase in the continentality of the clouds, and by a lack of rain-producing clouds. Moreover, prolonged drought periods usually result in heat waves, which are equally associated with high-pressure systems, subsidence, and stability in the atmosphere and extremely high temperatures.

Heat is acquired by the body by several physical properties, such as temperature, wet-bulb temperature, ventilation, solar radiation, and long-wave radiation, among others. For the use in weather forecasting and climatology, the statistics of these parameters are mostly evaluated separately. As expected, the humid tropical regions show an occurrence of heat waves on more than 300 days/year, permanent residents mostly being acclimated and prepared to cope with the endemic heat conditions. In the midlatitudes, the occurrence of such days ranges between about 20 and 100 days. In the midlatitudes, the days with heat stress mainly occur in the summer season and are grouped in sequences of days, in heat waves, mostly exceeding long-term mean temperatures. Following the midlatitude weather patterns, often heat waves last for 2–5 days. This duration is closely connected to the basic properties of midlatitude weather, dominated by transient high- and low-pressure systems. The intensity or severity of any particular heat wave depends on the temporal and local peculiarities of the pressure systems—in rare cases, allowing a heat wave to last for weeks and create particularly hot conditions. The duration is of some relevance because it takes a few days for the heat to penetrate the walls of most types of standard non–air-conditioned buildings and raise the indoor temperature to that outside.

Taking our body temperature as base temperature, a simple definition of a heat wave would be when the temperature of the environment rises above the body temperature of 37°C, but we must also take into account several other meteorological factors besides temperature. The heat wave threshold temperature will also vary from region to region and from season to season. There are some places in the world where the outside temperature never exceeds 37°C, still sometimes, the term heat wave can be used for unusual high temperatures observed there. The duration of the extreme values in temperature must be also considered. Temperatures in excess of 40°C for a long period during the day result in the weakening of the human body. The situation worsened on engaging in activities, especially in labor works. Most vulnerable are the elderly and babies.

9.4.1 Heat Waves Frequency Analysis

Taking the daily maximum temperature of above 35°C as threshold, the number of days with this temperature is identified for each station. If successive days have maximum temperatures above 35°C, they are identified as one heat wave episode, with the number of successive days as the duration and the cumulative temperatures above 35°C reported during that period as the intensity or severity of the heat wave. Several episodes are grouped according their duration, for the whole period of study, and are ranked according to their intensity for each station.

The frequency of an extreme event is usually expressed by its return period or recurrence interval, which may be defined as the average interval of time within which the magnitude of the event is equated or exceeded once. The magnitude of an extreme event is given by the absolute maximum temperature occurring for a particular duration, and data for extreme events can be usually presented by SDF graphs for several points throughout the region of interest. For the estimation of extreme events, such as heat waves, in which the return periods are required as input, when the intensities and duration are given, it is necessary to assume a particular mathematical form of the frequency distribution. Several theoretical distributions have been tested against the cumulative intensities of extreme phenomena of various durations. These include the Extreme Value I (EVI, Gumbel), the Generalized Extreme Value (GEV), the three parameter Log-Normal (LN3) and the Log-Pearson (LP3) distributions [1,13]. Application of the nonparametric Kolmogorov–Smirnov two-sample tests at 95% confidence level and visual inspection of the fitting of the theoretical frequency distributions to cumulative intensity values indicate that the EVI provides, overall, a reasonable and acceptable approximation of the frequency of the calculated intensity values [1]. Furthermore, the EVI has been used in numerous extreme phenomena studies [13]. A brief description of the steps, which are followed to develop the SDF relationships, is presented.

Data used in this study include daily series of maximum temperature from 13 meteorological stations in Greece. The geographical distribution of the stations is delineated in Figure 9.4. The study period for each station examined is given in Table 9.4. Only the dry-bulb temperature, as reported from the meteorological stations, is used. The threshold temperature is temperature above 35°C.

Step 1: *Probability Tables*—The episodes for each station are identified when the maximum temperature for successive days exceeds 35°C. Cumulative temperatures over 35°C of each episode are used in order to rank the episode's intensity. In this way, multiple episodes for the whole period are calculated for several durations. In the table, column 1 shows the ranking numbers; column 2 shows the maximum temperature values in ascending order; column 3 shows the corresponding probability (P) of occurrence using the Weibull plotting position equation, where m is the current ranking number and n is the total number of data points; and column 4 shows the corresponding return period T duration using the equation where P was previously defined. Table 9.5 provides an example probability table for Larissa station for 6-day duration heat wave episodes.

FIGURE 9.4 Map of Greece with 13 stations used in heat severity–duration–frequency analysis. (From Bampzelis, D. et al., Severity-duration-frequency relationships of heatwaves in Greece, in: *Proceedings of the Third HAICTA* (*Hellenic Association of Information and Communication Technologies for Agriculture*) *International Conference*, Volos, Greece, September 20–23, 2006, pp. 1055–1061.)

TABLE 9.4 Database of Stations of the Map of Greece of Figure 9.4 Used in Heat Severity–Duration–Frequency Analysis

Stations Used for Period 1955–2000	Stations Used for Period 1963–1982
1. Larissa	6. Agrinio
2. Irakleio	7. Arta
3. Athens (Helleniko)	8. Korinthos
4. Ierapetra	9. Ioannina
5. Rhodos	10. Kalamata
	11. Chania
	12. Patra
	13. Tripoli

TABLE 9.5 Probability Table of Duration of Six Successive Days of Cumulative Maximum Daily Temperature above 35°C for Larissa Station

Rank	Cumulative Temperature (°C)	Probability P	Return Period T (Years)
1	30.6	0.059	17
2	26.2	0.118	8.5
3	25.8	0.177	5.67
4	24.2	0.235	4.25
5	21.2	0.294	3.4
6	18.6	0.353	2.83
7	16.2	0.412	2.43
8	13.2	0.471	2.13
9	12.0	0.529	1.89
10	11.8	0.588	1.7
11	11.6	0.647	1.55
12	10.3	0.706	1.42
13	8.2	0.765	1.31
14	6.4	0.824	1.21
15	5.0	0.882	1.13
16	5.0	0.941	1.06

Step 2: *Fitting Gumbel Distribution*—For each episode, the identified maximum temperatures are plotted versus the corresponding return periods and a statistical distribution is fitted to the plotted data points. Specifically, the extreme value law is used by fitting the EVI distribution [1], which has the following cumulative distribution function (Equation 9.11):

$$F(x) = \exp\left[-\exp\left(-A \cdot (x - U)\right)\right] \tag{9.11}$$

where A and U are the fitted parameters, which are computed for each duration from the data. The procedure of fitting the EVI distribution is applied to all the identified episodes for each station. An example of fitting the EVI curves for Larissa station is shown in Figure 9.5 for durations from 1 day to 9 days. As expected, each curve is plotted on top of the previous since it corresponds to ascending duration.

Step 3: *Severity–Duration–Frequency* (*SDF*) *Curves*—Finally, using the Gumbel distribution, cumulative heat wave periods are computed, which correspond to return periods of 2, 5, 10, 25, 50, and 100 years, respectively, for each identified heat wave duration, as seen in Figure 9.6 for Larissa station.

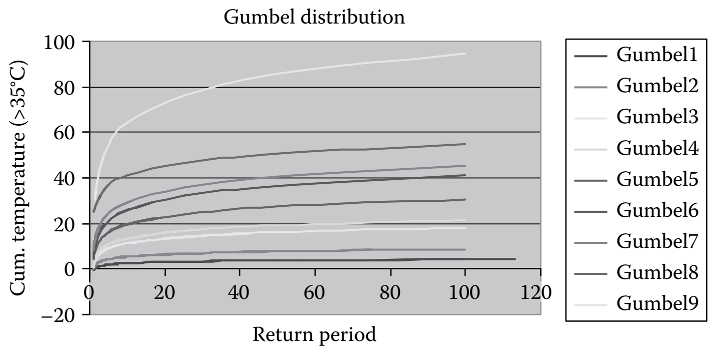

FIGURE 9.5 Fitted Gumbel distribution from 1 to 9 days' duration for the total number of heat waves episodes for Larissa station. (From Bampzelis, D. et al., Severity-duration-frequency relationships of heatwaves in Greece, in: *Proceedings of the Third HAICTA* (*Hellenic Association of Information and Communication Technologies for Agriculture*) *International Conference*, Volos, Greece, September 20–23, 2006, pp. 1055–1061.)

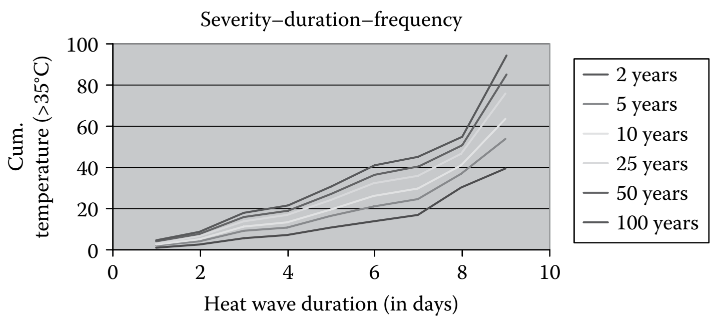

FIGURE 9.6 Severity–duration–frequency (SDF) curves for Larissa station. (From Bampzelis, D. et al., Severity-duration-frequency relationships of heatwaves in Greece, in: *Proceedings of the Third HAICTA* (*Hellenic Association of Information and Communication Technologies for Agriculture*) *International Conference*, Volos, Greece, September 20–23, 2006, pp. 1055–1061.)

In this study, a different approach for the term "heat wave" is used by creating SDF curves for several stations across Greece, taking into account only the dry-bulb temperature. The SDF curves appear as expected, since for decreasing frequencies, there is a corresponding increase in severities or intensities. In addition, Figures 9.7 through 9.9 show the heat waves SDF curves for Agrinio, Helliniko (Athens), and Ierapetra, respectively. There is a corresponding increase in severities of heat waves, respectively, which tends to become asymptotic to the *x*-axis, as seen in Figures 9.6 through 9.9, respectively. The SDF curves for the 13 stations in Greece clearly indicate that cumulative temperatures in continental stations, such as Larissa, Agrinio, and Tripoli, are much higher than those in coastal stations, such as Chania, Irakleio, and Rhodes (Figure 9.10). Thus, continental stations are more vulnerable to heat waves than coastal stations, as expected. In Figure 9.4, the cumulative temperatures for the 13 stations can be seen for a 4-day heat wave duration and a 100-year return period. The expected cumulative temperatures for several heat wave durations can be helpful to farmers when planning their crops and for irrigation and water needs. Results are also useful in producing iso-severity maps for Greece and in agroclimatic design and planning.

9.4.2 HEWS: Heat Waves Early Warning Systems

Heat waves monitoring is based on the development of HEWS. Heat waves hazard is based on temperature and its spatiotemporal variability. Quantification of heat waves hazard uses a methodological approach based on the maximum temperature consideration [1,71]. The database consists of a series of

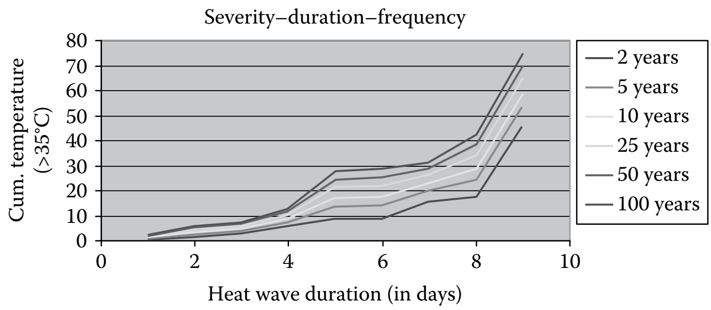

FIGURE 9.7 Severity–duration–frequency (SDF) curves for Agrinio station.

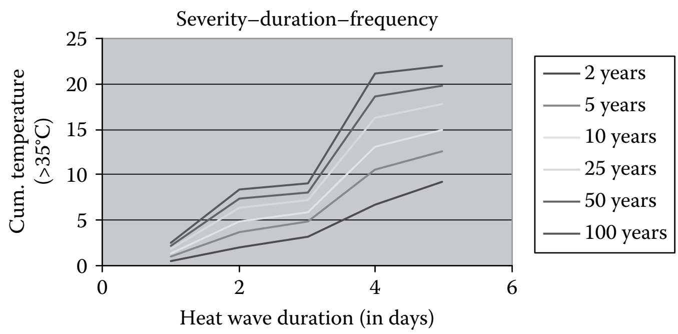

FIGURE 9.8 Severity–duration–frequency (SDF) curves for Helliniko (Athens) station.

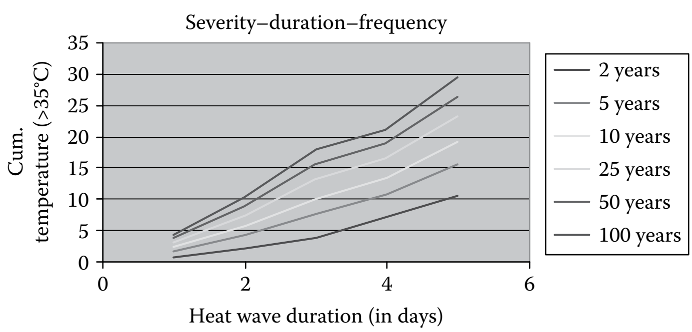

FIGURE 9.9 Severity–duration–frequency (SDF) curves for Ierapetra station.

satellite records (e.g., LANDSAT, METEOSAT, NOAA/AVHRR) from which temperature is extracted on a pixel basis. For monitoring heat waves, a so-called phenomenological approach is used based on Kalman filtering [2], which comes under estimation and control theory. Specifically, a one-step-ahead forecasting on a pixel basis using 2D satellite temperature images is considered. In this way, temperature time series are developed for each pixel and then the one-step-ahead forecasting is attempted. The adopted approach comes from the optimal estimation theory, and in the current application, the adaptive Kalman filter is employed [12]. Specifically, the system model is the so-called phenomenological temperature model that is based on the assumption that the daily variability in temperature follows a sinusoidal function.

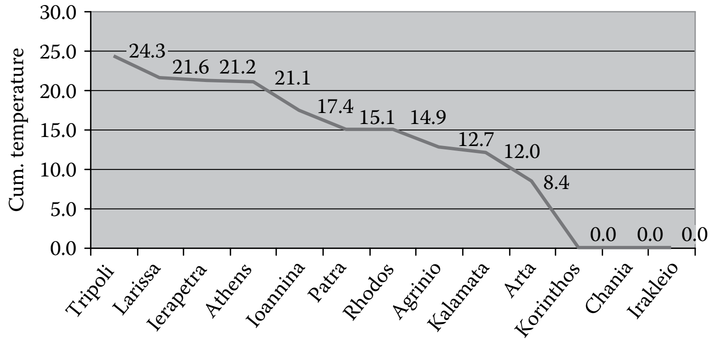

FIGURE 9.10 Cumulative temperatures above 35°C for all stations (100-year return period, 4-day heat wave duration). (From Bampzelis, D. et al., Severity-duration-frequency relationships of heatwaves in Greece, in: *Proceedings of the Third HAICTA* (*Hellenic Association of Information and Communication Technologies for Agriculture*) *International Conference*, Volos, Greece, September 20–23, 2006, pp. 1055–1061.)

9.5 Summary and Conclusions

This chapter discusses composite drought assessment and management and then develops a quantitative methodology for heat waves monitoring. At first, a brief description of cumulative hazards is presented, which include climatic hazards such as droughts and heat waves. This is followed by a presentation of composite drought concepts, types, quantification, indices, features, and assessment, which together constitute the first stage of the methodology. The second stage of the methodology includes the heat waves monitoring part, which includes the development of a heat waves quantitative classification scheme, the development of SDF relationships, and the development of HEWS. Specifically, composite drought assessment is considered on a monthly basis and the affected areas are identified. In the second stage, a heat waves frequency analysis is conducted. Finally, a methodology for heat waves monitoring is developed for the affected areas on a daily basis. This quantitative methodology for heat waves frequency analysis and monitoring within specified areas affected by drought constitutes a very useful contribution to the field since it allows a better understanding of the factors and causes of heat waves, thus leading to the development of potentially effective mitigation measures. Needless to say, much work remains in terms of monitoring and preparing for heat waves and understanding causal interactions, as well as in terms of capacity building.

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10

Drought and Pest Management

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Abstract Drought obviously favors pest attacks. A pest attack occurs under conditions of dry and warm weather. To diminish the drought impact on pest attacks, the application of seed chemical treatment for soil pests is employed and the application of modern crop technologies for other pests. By correct warning and chemical application under best conditions, the crop is protected against pest attack. To protect the yield against pest attack, the crop state and pest density need to be assessed. Taking into consideration the elements that characterize the host plant-pest, specific chemical treatments need to be rapidly implemented on all damaged areas. The decision to apply chemicals on certain areas has been difficult due to a reduced yield level, and the treatment cost may be too high compared with the expected income. Treatment will depend on the species and the position of the nest. Efforts have been made by countries' governments to further the work of feral animal and pest management projects in drought-affected areas. The funding has given a boost to local delivery organizations whose work helps to manage the impact predators have on grazing animals during drought. During drought, pest and feral animals add further pressure to pastures and groundcover at a time when feed is critical for livestock. Drought Pest Management brings many years of combined experience and knowledge to provide reliable and thorough assessments and eradication of any pest infestations. The Transitional Farm Family Payment assists farm families who are experiencing financial difficulty in managing the impacts of climate variability and market fluctuations regardless of location. The pilot can test a range of alternate drought reform measures that are developed in response to the review of drought policy.

10.1 Introduction

10.1.1 Background

Droughts are a major hazard to both natural and human-dominated environments and those, especially, of long duration and high intensity can be highly damaging and leave long-lasting effects. Previous works describe the climatic conditions that give rise to droughts and their various forms and chief attributes [1,2]. Past droughts are described including those that had severe impacts on human societies. As a disturbance, droughts can be thought of as "ramps" in that they usually build up slowly and take time to become evident. As precipitation is reduced, flows from catchments into aquatic systems decline. As water diminishes in water bodies, there is a change in ecological processes and the biota can be drastically reduced, though species and populations may survive by using various refuges. Recovery from drought varies in both rate and degree of completeness and may be a function of both refuge availability and connectivity. Agricultural droughts are events that become the next phase of meteorological droughts. As the name implies, a drought of this nature will extend in duration to the point at which the agricultural concerns of a region are being impacted by dryness and lack of adequate soil moisture [1,7,10,11]. Agricultural drought may extend into more than one growing season, but the natural break between seasons is identified as a period where drought does not worsen or improve, because no agricultural production takes place (such as in the winter season). Agricultural drought can also precede the actual start of the growing season in which conditions are not favorable for planting because of dryness and the lack of soil moisture, or there is not enough moisture available for pasture and rangelands to green up [6,13–15,17]. Hydrological drought, as the name implies, refers to drought events that curtail the amount of water available in rivers, streams, lakes, reservoirs, and groundwater [2,28,29,37–40,42]. Other weather or climate factors can play a role in certain goods not being available, but in socioeconomic drought, the demand for these goods exceeds supply because of drought. Socioeconomic drought impacts can develop immediately once drought advances into a region and may linger for quite some time depending on the severity of the impact and the importance of the goods being impacted in the region. Agricultural droughts can be characterized as an extended meteorological drought during which there is a deficiency of precipitation during the growing season such that crop growth and development are suppressed. Agricultural drought can also be associated with a dry period prior to the growing season in which soils are not fully recharged with moisture, which carries over to a growing season with inadequate precipitation, especially during critical crop growth stages. It may also include periods when water for irrigation is lacking [2,25,43–46]. As meteorological droughts are prolonged, the lack of runoff from precipitation events due to dry soils begins to impact the hydrology of a region. There is typically a lag involved that is unique to each region and for a particular time of the year as the impacts to hydrology are not seen immediately after the start of the drought. With an extended dry period, soil moisture diminishes, surface runoff and subsurface recharge are reduced, and the amount of water in the hydrologic system of a region declines. During winter months, frozen precipitation is accumulated for future runoff, so a dry winter can induce hydrologic drought months later. Even with precipitation, the dry soils can inhibit substantial runoff, as they capture excess moisture before it is able to reach rivers, streams, and reservoirs. Dryness and heat (via evaporation) work together to reduce the amount of water available in hydrologic systems. As some hydrologic systems are managed, water managers can choose to withhold water if hydrologic drought is of concern to try to lessen future impacts. Without proper recharge, a long-term drought will impact the hydrology of the region even after precipitation returns to normal levelsp [30–36,41]. It typically takes the longest time period for a hydrological drought to develop and, in turn, the recovery time can also take months or even years [24,25,28,29].

In many parts of the world, global warming may result in increases in the duration and intensity of droughts. Drought is an extended period—a season, a year, or several years—of deficient rainfall relative to the statistical multiyear mean for a region; in other words, it is an extended period of below-average rainfall. Most of the time, drought is detected when the observed three-month total rainfall is in the lowest 10% of the long-term precipitation record. This is called "meteorological drought" and it is determined by the "Rainfall Deciles method." Many studies have been carried out on climatic aspects of drought [4,9]. Drought is not the same as aridity (which is the situation found in arid and semiarid regions where annual rainfall is always expected to be little), though it has some similar effects.

At the start of a drought, the rainfall that is normally expected in that season fails to occur. The soil begins to dry out, there is no surface runoff, and no rain to recharge the groundwater. In the early stages of drought, temporary water bodies (such as ponds, wetlands) may dry up and temporary flowing waters (ephemeral creeks) may shrink and turn into a series of separate pools.

As drought builds, water levels and volumes decrease in natural perennial waters. Flowing waters (rivers, streams) may flow only slowly for extended periods. Eventually, the water stops flowing—a critical stage. Streams then become a series of pools and even these may disappear during severe drought. This is known as "surface-water drought." It is important to recognize that in severe drought the levels and volumes of groundwater will also fall. This is "groundwater drought," which is poorly understood (out of sight, out of mind). Groundwater drought diminishes the streams and wetlands that are normally kept wet by an inflow of baseflow (groundwater that flows from the ground into streams) during short dry spells. When normal rainfall returns, meteorological drought typically breaks before surface-water drought and well before groundwater drought. Throughout the semiarid lands of the Mediterranean, the Middle East, and India, many types of rural sociology, village or tribal structure, religious belief and prejudice, and methods of crop and animal husbandry can be found, but perhaps the outstanding factor which has played an important part in the destruction of vegetation, the prevention of its regeneration, and the increase of desiccation, in addition to pest attack, is the sociological distinction between the shepherd and the cultivator. As population and livestock numbers have increased, so has the conflict between the shepherd and the cultivator in the struggle for dwindling land resources in an environment of increasing desiccation, which is their common inheritance. The complexity of drought over different time scales, geographic regions, and dimensions for different users has resulted in the development of regionally focused information services within countries [4,6,27].

10.1.2 General Pest Information

There are hundreds of species of cockroaches including both native and introduced species. Thriving in warm, humid climates, cockroaches commonly infest Queensland homes wherever they can find moisture and a food source. Rapid breeders, cockroaches can become real pests very quickly. Redback spiders, the female of which is highly dangerous, build nests in dry, sheltered areas such as garden sheds and rubbish piles. Other species such as Huntsman, Funnel Web, and White-Tailed spiders thrive in leaf litter, garden beds, or burrows. Removal of spiders varies with each species and level of infestation. Ants are community-based insects that live in nests. Ants and their nests vary in size depending on the species. Ants generally become a problem when they are foraging for food or moisture and a large number of ants converge to transport the food back to their nest. Treatment will depend on the species and the position of the nest. Silverfish are nocturnal, small, soft, and wingless insects often found in the roof, linen cupboards, and carpets. They feed on a large variety of items in the home including flour, paper, glue, linen, sugar, etc., and can chew holes in stored linen and clothing. Rats and mice can transmit a variety of diseases to humans via fleas, bacteria, and droppings. Along with causing damage by gnawing on wood, wires, and fixtures, they can destroy vegetables, fruits, and crops. There are many varieties of fleas, which can become a big problem very quickly when eggs hatch onto pets, carpet, lawns, etc. Treatment is done through a blanket spray in the house and the surrounding lawns.

10.1.3 Drought Effect on Pest Attack in Field Crops

The evolution of invertebrates, including insects, is strongly influenced by ecological factors, especially temperature, and is closely linked with air humidity and soil moisture. As they are hetero-thermal animals, insects have variable body temperature, depending on the temperature of the environment in which they live, and the temperature changes influence both their body temperature and all vital processes, including the attack on plants and the damage level. Similarly, humidity directly or indirectly influences insects and modifies their behavior and prolificacy. The influence of these factors on pests is species dependent: there are species in which the evolution and especially the attack are favorably influenced by wet and cold weather, as well as species that are favorably influenced by dry and warm weather. Humidity deficit and high temperatures intensify pest attack, and due to plant debility the feeding increases to cover the nutrient and water needs, which increase because of hydric disequilibrium.

In the last half of the twentieth century, researches have been performed on frequent drought conditions. The behavior of some of the predominant pests was tested: for each pest and crop, the work method was different, keeping in view the evolution of the biological cycle and the manner of attack, as well as the fluctuation of the population level depending on the climatic factor. In order to emphasize the way in which drought influences pest evolution, some data are presented about the attack by the main pests under the conditions described.

The *sunn pest* is one of the main pests, whereby the attack by larvae and, under certain conditions, by adults contributes to quantitative and qualitative yield reduction. There is a disordered periodicity in the population level of this pest. After a continuous increase in the population, which reaches high densities causing significant wheat yield losses, a depression period follows, when the population level diminishes considerably. As observed, the adult attack was extremely strong, especially for wheat in the emergence/tillering stage.

The following factors influenced the attack intensity:

- Late emergence of wheat in autumn but especially in spring
- Continuous snow layer, without days with adequate temperatures for crop emergence
- Strong soil compaction, which unfavorably affected the wheat root growth in spring
- Very late spring with sudden warming and without rainfall, which did not allow vegetation recovery and increased plant debility; wheat plants were stressed due to high temperatures, heat, and superficial root system
- Increased aggressiveness of adults due to high temperatures

In agricultural years, small grains, especially wheat, have been dramatically influenced by the evolution of climate, which amplified the presence and attack of the sunn pest, as well as of other insects such as cereal flies, wheat thrips, and oat beetles, although these caused less damage. In the case of the sunn pest, the high population of biological reserve in autumn, illustrated by an increased density in forests, as well as normal mortality, with no influence on population level, was already a cause for concern. However, the virulent adult attacks, caused by environmental factors that influenced especially the plant and also the pest's biological cycle, substantially exceeded expectations. Several peculiarities of the wheat crop determined important consequences: reduction of cultivated areas, as many fields were abandoned and reduced plot density per square meter, below normal limits, determined by many factors such as poor plant establishment; plant loss due to frost, waterlogging, weak root system, or no tilling; late vegetation due to prolonged cold intervals; very late springtime, which did not allow the recovery of vegetation and accelerated plant debility, sudden warming and no rainfalls; and stagnation of growth determined by the lack of moisture around the roots, thus causing inefficient development of the root system. Plant loss was also determined by soil crust as well as by attacks by some pests (cereal flies, thrips, or oat beetles) and high temperatures that accentuated the weakness of the crop. Under these conditions, the migration of the sunn pest from forests to fields was rapid and, in a short period, onto the entire cultivation area. A strong aggressiveness of adults was noticed, determined by the following factors:

- There was a higher density of adults in crops as compared with previous years.
- The disparity between the early attack time of adults and the wheat's late vegetation stage reduced growth and hydric disequilibrium; increased aggressiveness of each adult due to high temperatures, which determined an excessively active rearing to cover both nutrient and water needs.

Keeping in view the elements that characterized the plant/pest, a rapid intervention to control the adult sunn pest is recommended. Thus, treatment against adults is necessary on all areas even for 1 individual/m^2, but the last chemical application had strong negative effects. The percentage of the attacked straw was very high at shooting-boot stage for crops with both reduced density and delayed vegetation. The reproduction ability is strongly influenced by temperature and rainfall, determining the variable level of populations and, implicitly, of attacks and damages. The negative impact of larvae and new adult attack on wheat quality is well known. To reduce this impact, chemical treatment on all cultivation areas with any density of sunn pest is required, normally depending on many factors, such as wheat cultivar, vegetation, climate condition, and fertilization; the yield quality is not affected by up to 2% pricked grains [23]. By correct warning and the chemical application under the best conditions, the crop is protected against sunn pest attack. To protect the yield against sunn pest attack, the crop state and pest density must be assessed. In relation with the host plant phenology, insect rearing began on grains from the first developmental stages, amplifying, in this way, the negative impact on yield and quality during the early biological cycle. Taking into consideration the elements that characterized the host plant-pest, chemical treatment needs to be rapidly applied on all damaged areas. The decision to apply chemicals on certain areas has been difficult due to a reduced yield level and the treatment cost being too high as compared with the expected income.

Wheat thrips are a common pest, but usually cause no significant damages. However, under excessive drought conditions, damages from strong adult thrip attack could be significant due to reduced plant densities.

Aphids and *cicads* could be dangerous pests in small grains under favorable conditions of temperature and heat, immediately after plant emergence. When drought is present, the early sowing and emergence of wheat and barley could coincide with optimum pest flight. Under these circumstances, the damages could be direct, by plant pricking and vacuolar juice suckling, or indirect, as vectors of various virus diseases and mycoplasms. Such situations were frequently observed, because of farmers' tendency to plant earlier as chemical treatment application was required to be done in autumn.

In the case of *carabid beetle*, one of the most effective and cheap methods to prevent pest attack is by crop rotation, by limiting small grain monoculture. But, due to various, more or less objective, factors, monoculture is hard to avoid, and wheat or barley monoculture can be found extensively each year. The pest is difficult to control, due to prolonged rearing and the harmful period of larvae. The high adaptation of carabid beetle to the host plant phenology and the significant role of humidity in its evolution are well known. The biological cycle begins during the sowing–emergence stage of winter cereals, when eggs are laid, and larvae occurrence and development coincide with the first stages of plant development. Under normal climatic conditions, with high soil moisture, the attack is more harmful when the rearing of larvae begins earlier, after plant emergence, and young plantlets are rapidly destroyed before shooting. Under these circumstances, spots that are completely destroyed remain thus until winter. In the years with a dry season, the dry soil makes larvae rearing and development more difficult and the attack occurs later, after the first rains, with no obvious damages. The late attack in spring is less visible, because the plants have a high biomass, a fact that camouflages the damage and ensures better survival of the attacked plants. If the emergence takes place in winter, the pests feed on weak plants and the attack is also strong. Another atypical situation can be found in early winters when the attack is very late but extremely virulent on untreated areas. One can conclude that the carabid beetle attack is under the strong influence of climatic factors. Under these conditions, the protection against carabid beetles can only be achieved at an optimum level, by preventive chemical treatment (such as to wheat and barley), using a product that can ensure adequate protection.

Maize leaf weevil represents the most harmful pest of maize and sunflower crops. The attack during the first vegetation stages frequently leads to yield reduction or crop destruction. Being thermo- and xerophilous insects, they are widely spread, especially in the arid and semiarid areas of Romania, and the adults are very active at high temperatures and low humidity while low temperatures and high rainfall greatly interfere with their activity. Historical data show that the attack by maize leaf weevil completely destroyed the plant due to reduced rainfall, and the attack was very strong, with maximum or close to maximum values. However, higher rainfall reduced the intensity of attack. The same difference in the attack intensity was noticed in the case of saved plants too. In the years when the attack intensity was very high, the percentage of saved plants was very low or the crop was completely destroyed while in the years with higher rainfall, the ratio of saved plants was higher. Seed treatments with recommended systemic insecticides significantly reduced the attack, and up to 100% of the plants were saved. The attack produced by flea beetle varied widely depending on climatic conditions. Thus, high values of attack were recorded due to higher temperatures and low rainfall, while pest occurrence and attack were reduced during cold and wet weather. Treatments with approved systemic chemicals significantly reduced the attack, ensuring good protection of plantlets against flea beetle even in the case of a strong attack.

Cabbage aphid produces significant damage in rape crops. Grown on increasing areas in recent years, rape is confronted with a strong aphid attack, determined by excessive drought, which encourages high pest proliferation. Thus, aphid densities in 2001 were, in some cases, up to several thousand per plant, requiring chemical treatments on large areas. Because the most dangerous effect of the attack occurs especially during the first vegetation stages, it is necessary to correctly apply seed treatment with approved systemic insecticides to reduce drought influence on the attack. Correct crop management practices can help plants to better resist some pest attacks by reducing drought stress.

The main field crops (maize, sorghum, small grains, sunflower, rape, soybean) are always attacked by many harmful insects. Drought conditions encourage the population development and their attack, amplifying yield losses; higher aggressiveness of the insects is determined by the increased need to extract water from weak plants. In maize and sunflower, the warm and dry weather during germination–emergence obviously influences the attack of maize leaf weevil, its virulence leading to crop destruction over large areas. The attack produced by sunn pests of cereals is strongly influenced by climatic conditions; the drought effect amplifies damages up to wheat crop destruction on large areas. Drought has the same amplifying effect on the attack of other pests on small grains (thrips, aphids, cicads, stem sawflies), sorghum (green bug aphid), linseed (flea beetle), or rape. Good results in reducing drought effect on soil pest attack are obtained by seed chemical treatment with approved systemic insecticides that have good solubility. Correct crop management practices could contribute to the alleviation of drought effect on pest aggressiveness.

Although some insects thrive in moist conditions, heat and drought can be the ultimate survival conditions for others. Some of the most common insects that cause problems during periods of heat and drought include *Aphids*. Alphide is the nonchemical control of plant pests. Aphids are insects of most concern in such conditions because their populations grow and cause increased stress on plants that are already stressed by heat and drought. In addition, growers often delay treatment, awaiting rainfall or natural disease, enabling the aphid populations to continue to build up. Aphids feed on plants for their sap. Although one or two aphids that are quickly eliminated may cause little to no damage, high and quickly developing populations can cause significant damage. Their feeding causes leaves to curl and yellow and shoots to become stunted. As a conclusion, drought obviously affects pest attacks, increasing their effect on crops. Drought produces the same effect in the case of other harmful pests too, such as beet rot weevil, sugar beet flea beetle, turnip flea beetle, hop flea beetle, and oats beetle on sunflower and soybean [1,5,16,19,23,28,31].

10.2 Pest Management in Line with Drought

The conventional focus of meteorological services on presenting information in the form of spatial weather maps may contribute to a continued focus on spatial technologies. Focus on spatial information is likely to grow as spatial technologies, remote sensing, and modeling capabilities continue to develop. However, a balance is required to ensure that improvements in spatial technology do not constrain the development of improved predictive methods for temporal forecasts. Potential users of drought prediction services expressed a preference for the bureau to provide rainfall forecasts and information on temperature and evapotranspiration across the country to allow local agencies to convert them into indices that could be used within their area of operation [8,18,20]. Confidence in data at all time scales is required to inform operational decisions in the agricultural sector in the short term and to guide the development of business risk profiles in the longer term. Such confidence would also serve in planning water storage operations for water supply. The government in each country is contributing millions to help reduce the impact of pest and feral animals on drought-affected farmers. The government has approved millions to further the work of feral animal and pest management projects already under way in drought-affected areas. The funding is giving a boost to local delivery organizations whose work helps to manage the impact predators have on grazing animals during drought. During drought, pest and feral animals add further pressure on pastures and groundcover at a time when feed is critical for livestock. In addition, wild dogs, feral pigs, and foxes tend to predate on grazing animals that are concentrated around fewer watering points. Drought Pest Management brings many years of combined experience and knowledge to provide reliable and thorough assessments and eradication of any pest infestations. Using the best pest treatments and following all industry protocols, the agency in charge of the Drought Pest Management should be committed to providing fast, reliable, and lasting results. Drought Pest Management is expected to additionally take care of any general pest concerns including cockroaches, ants, spiders, mice, rats, and silverfish, as well as providing fast and detailed Pre-Purchase Inspection reports. A complete general pest control service includes the identification of the specific pest, eradication with industry-approved treatments, and follow-up inspections when required, including household pests: termites, cockroaches, spiders, ants, rats/mice, fleas, silverfish, wasps, bees, lice, borers, and carpet beetles. Cockroaches, spiders, and silverfish are sprayed under the eaves, doorways, and windows and the inside perimeter including cracks and crevices, as well as spot treatment for spiders. Dusting is done in the ceiling via the manhole and in and around kitchen plumbing and white goods if required. Rats and mice are treated with baits placed in the roof and behind the refrigerator and washing machine. Ants, fleas, borers, etc., are assessed by technicians and treated according to each situation.

10.2.1 Drought Policy from the Perspective of Pest Management

A comprehensive review of drought policy includes a climatic assessment, a social assessment, and an economic assessment. In response to the review, a pilot of drought reform measures can be conducted covering a broad range of farming businesses and climatic conditions [3,12,21]. The Transitional Farm Family Payment assists farm families who are experiencing financial difficulty to manage the impacts of climate variability and market fluctuations regardless of location. The Transitional Farm Family Payment is available to eligible farmers. The pilot can test a range of alternate drought reform measures that are developed in response to the review of the drought policy. These are designed to conduct the following actions:

1. To support farmers in managing and preparing for future drought and climate variability
2. To increase the resilience and capacity of rural communities to cope with adversity
3. To better coordinate social support services in rural areas
4. To help families meet immediate basic household expenses during financial hardship
5. To connect current farmers and former farmers to discuss opportunities outside of farming

The range of measures in the pilot is designed to move from a crisis management approach to risk management [18]. The aim is to better support farmers, their families, and rural communities in preparing for future challenges rather than waiting until they face a crisis to offer assistance. Access to assistance was available to all farmers in the pilot region as long as they met the relevant eligibility criteria. The economic assessment review of government drought support found that interest rate subsidies often discouraged farmers from making difficult decisions about their future and did not reward farmers who used the profitable times to pay off debts. The drought reform measures in the pilot are designed to help farmers manage and prepare for future challenges, including a variable climate, rather than waiting for them to seek assistance.

The government's approach is guided by drought policy. Drought policy in the middle of the twentieth century focused on attempts to "drought-proof" agriculture through the expansion of irrigation. In the 1970s, most governments' policies shifted to recognize drought as a natural disaster, enabling support for those affected to be provided under the joint state Natural Disaster Relief and Recovery Arrangements.

In the 1980s, drought was removed from these arrangements and a review was undertaken, which determined that the previous drought policy was poorly targeted, and distorted farm input prices and worked as a disincentive for farmers to prepare for drought. The response to this review was the new Drought Policy [22].

The following are the objectives of this Drought Policy:

- To encourage primary producers and other sections of rural people to adopt self-reliant approaches to managing climate variability
- To facilitate the maintenance and protection of agricultural and environmental resources during periods of climatic stress
- To facilitate the early recovery of agricultural and rural industries, consistent with long-term sustainable levels

The Drought Policy describes the broad context of drought policy and sets out the government's overarching approach to the provision of support and assistance.

An agreement between the governments (federal, state, and local) outlines arrangements for the implementation of current programs relating to drought preparedness and in-drought assistance. The agreement is underpinned by the Drought Policy and aims to refocus government support to encourage farmers to prepare for droughts and to manage their business risks, instead of waiting until they are in crisis to offer assistance. While focusing on encouraging preparedness and self-reliance, the agency also includes guidance on the provision of in-drought assistance. Under the Drought Policy, a number of assistance programs can be introduced, including the Rural Adjustment Scheme, which offers grants and interest rate subsidies, and the Drought Relief Payment, which provides income support for farmers within declared exceptional circumstance areas. Other programs, including the Farm Management Deposits Scheme and the Rural Financial Counseling Service, can be established under the Drought Policy. A range of other support programs, not directly associated with the Drought Policy, are also available to farmers through the national and state governments. Most agreed that current approaches to drought and exceptional circumstances are no longer the most appropriate in the context of a changing climate. Drought policy needs to be improved to create an environment of self-reliance and preparedness and encourages the adoption of appropriate climate change management practices. Reviewing and improving drought policy in parallel with the development of climate change policies and programs will put farmers in the best possible position to meet the challenges of a changing climate. The government can conduct a comprehensive review of drought policy through three separate assessments. The review will support the development of policies to help better prepare farmers and rural communities for a changing climate. The review includes the following:

- An *economic assessment* of drought support measures
- An assessment of the *social impacts* of drought on farm families and rural communities
- A *climatic assessment* of the likely future climate patterns and the current exceptional circumstances standard of a 1 in 20–25-year event.

10.2.1.1 The Drought Pilot

The government, in partnership with the other stakeholders, is expected to conduct a pilot of drought reform measures. The pilot tests a package of new measures developed in response to the review of the drought policy. The measures are designed to move from a crisis management approach to risk management. The aim is to better support farmers, their families, and rural communities in preparing for future challenges, rather than waiting until they are in crisis to offer assistance.

10.2.1.2 About the Pilot and Its Measures

The Government, in partnership with relevant sectors, conducts a pilot of drought reform measures. The Pilot test a package of measures develops in response to the review of drought policy. The measures are directed at helping farmers to move from a crisis management approach to risk management. The aim of the pilot was to better support farmers, their families, and rural communities in preparing for future challenges, rather than waiting until they are in crisis to offer assistance.

The funds can be delivered through the relevant state and territory governments to local organizations in affected areas. These organizations will work with local farmers. Details concerning the allocation of funds to the states and territories are provided in the Project Agreement for Assistance for Water Infrastructure and Pest Management. Depending on conditions, funding may be further extended to pest management programs in other jurisdictions. Funding may be used for activities to manage pest and feral animal impacts, for example, landscape-scale baiting programs to control wild dogs and feral pigs. Funding for the lethal control of nonnative pest animals will depend on local circumstances. Some pest animals (e.g., rabbits) may be best controlled on an individual property basis. Control of predatory pest animals is usually best undertaken through coordinated landscape-scale actions, determined in consultation with landowners and relevant agencies and councils.

10.2.1.3 Pilot Measures

10.2.1.3.1 Farm Planning

Farm Planning provided courses for farmers to develop or update a strategic plan for their farm business. The plan identified priority activities to help improve the management and preparedness of the farm business in its respond to future challenges. The training covered the economic aspects of a strategic plan such as risk management and financial planning, social aspects such as personal and business goals, and environmental aspects such as managing the impact of a changing climate on production.

10.2.1.3.2 Building Farm Businesses

Completion of farm planning is a prerequisite for accessing grants under the Building Farm Businesses program. Grants to eligible farm businesses are available as two components: Business Adaptation Grants are for eligible activities identified in the strategic plan developed or revised through the Farm Planning courses, which help farm businesses prepare for the impacts of drought, reduced water availability, and a changing climate; Landcare Adaptation Grants are for eligible activities identified in the strategic plan with a natural resource management focus, which has broader public benefit.

10.2.1.3.3 Stronger Rural Communities

The program can provide grants to local government authorities and community organizations to fund projects that build the resilience of rural communities and help them manage hardship resulting from an agricultural downturn. Government can provide an alternative suite of community and family support pilot measures for individuals, businesses, and communities.

10.2.1.3.4 Farm Social Support

The aim of the Farm Social Support measure is to provide a better coordinated social support network to meet the mental health, counseling, and other social needs of farming families and rural communities. Three initiatives are available through Farm Social Support:

1. Rural Support Initiative via Department of Human Services, where Rural Services Officers and social workers work to improve outreach services to rural communities.
2. Online Counseling for Rural Young People Initiative through an online counseling and information service for young people in the drought pilot region, which can be administered and funded by Rural and Regional Family Support Service through practical support from counselors, psychologists, and community welfare workers who help farmers work through issues and concerns and deal with relationship problems.
3. Farm Family Support provides income support for farmers facing financial hardship, allowing them to meet basic household needs. Recipients may also receive case management to assist them in developing a plan to identify steps to improve their financial position either on or off the farm.

10.2.1.3.5 Farm Exit Support (Including Advice and Training)

Farm Exit Support (including advice and training) provides assistance to support farmers in significant financial difficulty who decide to sell their farm and leave farming. This assistance helps farmers and their families to make a fresh start. In accepting a Farm Exit Support grant, farmers agree not to own or operate a farm enterprise within specified years from the date of settlement.

10.2.1.3.6 Beyond Farming

Beyond Farming, to be delivered by Social Services, puts farmers in touch with trained former farmers, to talk about opportunities outside of farming. It enables them to talk to someone who has been in the same position about the options for themselves and their families if they sell the farm business or retire. Former farmers may not provide advice, but can share their experiences and provide information on relevant services and assistance.

Exceptional circumstances are rare and severe events outside those that a farmer would normally be expected to manage using responsible farm management strategies. Specifically, they are events that occur on average once every 25–30 years and have an impact on income for a prolonged period (e.g., greater than 12 months). To be classified as an exceptional circumstance, the event must not be predictable or part of a process of structural adjustment. When an area or region is "declared" as experiencing an exceptional circumstances event, it triggers short-term support for farmers in situations beyond the scope of normal risk management.

Communities or peak industry groups must approach their state or territory government in the first instance. When the state or territory government is confident that the event and the case fully meet the exceptional circumstances criteria, the state or territory can then lodge an application for exceptional circumstances assistance with the relevant government minister. Once an area is declared as experiencing exceptional circumstances, eligible farmers can apply to receive exceptional circumstances Relief Payments. They can also access their Farm Management Deposits within 12 months of lodgment without losing their tax benefits, if they had made the deposit before the declaration. The Rural Advisory Council reviews declared areas before their expiry date to assess whether an extension to the declaration is warranted. The exceptional circumstances review criteria differ from the exceptional circumstances criteria and take into consideration whether seasonal, agronomic, and resource conditions have provided an opportunity for the majority of producers within the declared area to begin typical farm management practices relevant to their enterprise type and production cycle.

As part of the review, the Rural Advisory Council assesses information from a number of sources, including analyses by the Bureau of Agricultural and Resource Economics and Sciences (or similar ones), state and territory governments, and local producers. Additionally, the Rural Advisory Council may undertake an on-ground inspection of the area. If the Rural Advisory Council assesses an area as no longer being in exceptional circumstances, and the minister accepts the advice not to extend the declaration, assistance ceases on the date the declaration ends. The Rural Financial Counseling Service will provide free financial counseling to primary producers, fishers, and small rural business owners who are suffering financial hardship and have no alternative source of impartial support. The Rural Advisory Council will conduct a review of the rural financial counseling service program to assess the need and awareness of the service, its effectiveness, current structure, and future role [20–23,26].

10.3 Summary and Conclusions

Conventionally, drought is defined based upon the effect it has on people's lives. Commonly, there are four types of droughts: meteorological drought, surface water drought, groundwater drought, and soil-water drought. Meteorological drought occurs when there is a significant decrease in rainfall from the normal value over the area. Agricultural drought occurs when soil moisture and rainfall are inadequate during the growing season to support healthy crop growth to maturity and cause crop stress and wilting. Hydrological drought may be a result of a prolonged meteorological drought resulting in marked depletion of surface water and consequent drying up of reservoirs, lakes, streams, and rivers, cessation of spring flows, and decrease in groundwater level. There is a need for reorienting the drought approaches from a sustainable livelihood perspective, where the local and regional understanding becomes important. Drought monitoring can generally inform the broader policy development for pest management and has been an important planning instrument. Drought monitoring and prediction of pest attack are required to effectively manage the risks from pests via drought adaptation. Many sectors of the community would benefit from a comprehensive drought-monitoring and prediction service; however, such a service does not currently exist in many countries. Drought has a big impact on the environment and agricultural production, and the system in place needs to monitor and predict drought and rainfall deficiency. More comprehensive outlooks are provided by a global approach coupled with a regional and area-wise approach; hence, it must address the needs of the community as feedback to researchers and service providers, mainly in drought monitoring, prediction, drought risk reduction and management, drought early warning services, and sharing best practices.

The most severe social consequences of droughts are found in arid or semiarid regions where the availability of water is already low under normal conditions. Drought research and operational applications have been lagging behind in the development of pest-attacked areas. There is an urgent need both to address emerging issues in drought research and management and to interact with the scientific and operational communities, as well as policy-makers and the larger public, to raise awareness about potential drought hazards related to pest attack. Experiences have shown that working with people's institutions both at village and regional levels goes a long way in planning, implementation, and tackling pest attack on a long term. Drought has been viewed as an event that relates intricately to the livelihoods of the communities, and pest management happens to be one of the most effective methods to cope with drought. People have evolved their skills in handicrafts as an effective means of coping with perennial drought conditions wherein "water-dependent agriculture" is reduced to a supplementary source of income and worsened due to pest attack. Keeping the people at the center of this approach, agencies work through people's institutions to address pest management conditions from a sustainable livelihoods perspective.

This chapter discusses some perspectives on drought and pest management. The initiatives are to consider the range of options in managing pest-related drought from farm social support, drought policy, drought pilot, farm planning, beyond farm planning, and related topics. The chapter presents a synthesis of drought and pest management, as pest species are often favored by dry and warm weather in field crops. Data on maize leaf weevil, sunn pest, wheat thrips, wheat stem sawflies, some aphids and cicads, and ground flea beetle are presented to illustrate the influence of weather. The data show the favorable effect of drought on these pest attacks. The attack intensity increased under conditions of dry and warm weather as compared with conditions of cold and wet weather. To diminish the drought impact on pest attacks, satisfactory results can be obtained by the application of seed chemical treatment for soil pests and by the application of modern crop technologies for other pests.

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11

Groundwater Management in Drought Conditions

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Abstract This chapter analyzes the relevance that groundwater management acquires in drought conditions and discusses the role that it may have in the mitigation of the negative effects associated with such a phenomenon. The opportunities for groundwater exploitation constitute alternative water use, favored by the volume stored in aquifers in different regions. Drought events have increased lately, intensifying the requirement for groundwater, in particular for human consumption and agricultural use. The conjunctive use of surface water and groundwater is a technique of interest in many locations. During wet periods, the use of surface water prevails, leading to the recovery of the aquifer reserves, which are exploited more intensely during the dry periods. A groundwater reservoir appears as a strategic resource depending on its storage capacity, the availability of reserves, and its spatial distribution. Groundwater use entails a planned exploitation that takes into consideration environmental sustainability, based on the integrated management of the water resources. In order to do so, the key is a balanced use that avoids the excessive lowering of the groundwater levels (i.e., the depletion of the resource) and the deterioration of the chemical quality. An integrated management of the water resources in times of drought should be characterized by an adequate hydrogeological knowledge and their relationship with the natural ecosystems. An effective system to solve the problems resulting from droughts must implement preventive measures that would make it possible to count, well in advance, on the necessary infrastructure for groundwater supply, as well as monitoring and maintenance, which guarantee its availability if necessary.

11.1 Introduction

Droughts are natural catastrophes with dire consequences for society, especially due to the impact on the drinking water supply and the decrease in agricultural productivity. Unlike other catastrophes, such as floods, hurricanes, or tornadoes, whose distributions are rather restricted on a spatial and temporal scale, drought regimes are more difficult to determine as regards their duration, and their area of influence may be much larger. This leads to greater difficulties in defining the estimation and prediction methods.

Droughts have been classified into different types [18], such as meteorological (lack of precipitation), agricultural (lack of soil moisture), or hydrological drought (reduction in runoff or groundwater levels) [19].

For a given period of time, water deficiency may constitute a different type of drought depending on the effects taken into consideration. A prolonged dry period may significantly reduce crop yield (agricultural drought) due to the shortage in soil moisture [8], but have little effect on the storage of the groundwater recharged in previous periods. Conversely, during a dry period extended in time due to a lack of groundwater recharge, the water tables may be lowered, decreasing the reserves (hydrological drought), which may contrast with the occurrence of precipitations during the time period considered [12]. Examples may be given of the co-occurrence of agricultural drought due to the limited soil water reserves and of waterlogging caused by the rise in the water tables recharged in earlier times [13].

If groundwater is part of the water cycle, it constitutes an areally limited, renewable resource naturally recharged by the infiltration of rainwater or surface water. It is in continuous motion in an aquifer medium, though generally slowly, until it discharges through springs, rivers, or subterraneously into the sea; therefore, many aquatic and terrestrial ecosystems depend upon it.

The unity of the water cycle and the need for integrated water management entail taking groundwater into consideration during drought periods, given the role that it may have in the mitigation of the impact exerted by the phenomenon. It is precisely the objective of this chapter to define the importance of groundwater management in drought conditions.

11.2 Groundwater as Reservoir

An aquifer constitutes a subterranean water reservoir with different possibilities for use and exploitation, which is why they are a source of supply both during normal periods and droughts.

Groundwater systems tend to respond more slowly to short-term variability in climatic conditions than surface water. As a result, the estimation of groundwater storage and its related model simulations are generally based on average conditions, such as mean annual recharge or mean annual discharge into rivers. This use of the average conditions may be adequate in normal circumstances, but the results may be altered during droughts. Therefore, the simulation of extreme scenarios of water shortage is required.

Groundwater exploitation underwent extensive development in the second half of the twentieth century, which transformed groundwater into a significant source to mitigate the consequences of droughts. Experience suggests that traditionally such mitigation is associated with the construction of hydraulic infrastructure, such as surface reservoirs or canals for inter-basin water transfer.

In order to exploit groundwater during periods of droughts, it is necessary to take advantage of the possibilities for water transfer and storage that aquifers have to offer. The size and inertia of most aquifers cause them to function as large reservoirs with stored volumes several times larger than the annual recharge they receive [15].

The occurrence in different regions of groundwater reservoirs that store important volumes and whose exploitation is minimal is a practical alternative for drought mitigation.

On the other hand, in those regions where the groundwater levels have been drawn down significantly by exploitation before the drought, groundwater may fulfill a different role when dealing with droughts. Intensive exploitation may cause the water level in lakes and the runoff in streams and other water bodies to be below the limits during droughts [11], which constitutes an additional problem in such a situation.

The increase in groundwater use may continue after a drought, since constructing wells and setting up the infrastructure to supply groundwater may require substantial investment. Therefore, a drought might bring about an unexpected permanent change in the level of groundwater development.

The effect of possible long-term climate changes, including changes in the average conditions and climate variability, should also be considered [3,14]. Climate change could affect groundwater sustainability in several ways, including changes in recharge, longer-lasting droughts, changes in evapotranspiration, and the possibility of an increasing water demand. Shallow aquifers, which discharge most of the water flow in streams, lakes, wetlands, and springs, are the part of the groundwater system most sensitive to climate change.

11.3 Groundwater Use during Droughts

Water scarcity is a phenomenon that is becoming more frequent and alarming, and it affects different regions in the world. The number of drought events has grown, their severity has increased in the last 30 years, and—as previously mentioned—according to the climate change predictions, problems such as water shortage and droughts could be exacerbated [23,24].

The circumstantial use of groundwater due to a lack of water availability during droughts should also be associated with an increase in its exploitation. Such an increase is related to a larger demand brought about by the transformation of agriculture from rainfed to irrigated systems and by an increase in human population.

Groundwater pollution is much more difficult to abate than surface pollution because groundwater can move great distances through unseen aquifers. Pollutants and contaminants can be removed from groundwater by applying various techniques, thereby making it safe for use. Groundwater treatment techniques span biological, chemical, and physical treatment technologies. Nanotechnology is being used to develop solutions to different problems in groundwater quality. Nanoparticles can be used to convert the contaminating chemical through a chemical reaction to make it harmless [7].

The pollution hazard of an activity will be greater in certain hydrological, geological, and soil situations than in others. When we consider the level of risk from any given activity and want to ascertain its acceptability, we have to assess the total exposure of the groundwater system to that hazard. Vulnerability maps [21] are usually a significant element of the risk assessment.

Regions that satisfy their demand by using surface water generally have a hydraulic infrastructure with regulation capacity that allows them to guarantee the supply in normal climatic conditions, but during drought periods—when significant supply failures occur—they could be affected. Such a situation could be alleviated if groundwater were part of the exploitation system, since groundwater reserves are less affected by droughts in the short and medium term due to the characteristics and hydraulic properties of aquifers.

In such cases, the role of groundwater has generally been a quick-fix solution to the problematic situation, but not as part of an integrated plan for a supply system, leaving its resolution up to more conventional operations. The proposal should include groundwater as another element in the regulation systems, taking into consideration that it is a resource whose availability is only temporarily affected by the consequences of an important decrease in precipitations.

Experience shows that in those regions that only depend on groundwater for supply, an overexploitation during drought periods may have a negative impact, even though groundwater constitutes a strategic resource in such situations.

In such regions, groundwater is more susceptible to the impact of drought, due to a reduction in natural or artificial recharge, but essentially because such conditions cause an increase in groundwater exploitation, with more extraction to compensate for the shortage in water supply. Although there may be groundwater management programs, in many areas there is no control that leads to restricting or prohibiting any groundwater pumping. Therefore, an increase in pumping may have negative consequences, including the drying of wells, the occurrence of subsidence, a decrease in water quality, saline intrusion, and the progressive depletion of the source [1]. As a result, apart from leaving the problem unsolved, it poses an excessive, unjustified economic burden.

Artificial recharge with rainwater or reclaimed water is the practice of increasing by artificial means the amount of water that enters a groundwater reservoir. This includes, for example, direction of water to the land surface through canals, irrigation furrows or sprinkler systems, and injection of water into the subsurface through wells.

The combined or alternating use of surface water and groundwater, which has been implemented in many regions [22], should have a much more significant role in the future [2]. The experience of developed countries, such as the United States [16], regarding such a practice shows that, though necessary, it takes time for it to prevail.

From a practical standpoint, it is possible to find an increasing number of examples of the importance of groundwater in drought management. This concept was put into practice in the southeastern United States (California) and also in Spain [4]. In each case, the technical aspects of the aquifer must be studied in order to find the most adequate type of recharge and storage, as on many occasions there are underlying economic, legal, and political problems. This may be the reason why the conjunctive use has not been implemented in a planned, supervised, and controlled manner in many locations.

This practice has been in use in many places worldwide. During wet years, surface water is used and the aquifer is allowed to recover in a natural way, whereas the "natural" groundwater is only extracted in the dry years. This type of solution has been applied in Arizona [15,17], and for a long time it has been demanded in order to solve problems in a rational way. In arid and semiarid areas, rainwater storage is essential to reduce the impact of persistent intraseasonal drought and also to reduce flood damage. This keeps water from undergoing evapotranspiration, increases groundwater level, and decreases flood hazards, modifying the exchange between surface water and groundwater through flood spreading, dams, etc. [10].

11.4 Groundwater in Water Management

The use of groundwater to mitigate the effects of droughts will be effective if it is developed on the basis of early planning, since it is an essential aspect to maintain the reliability and sustainability of the resource. The components of the plan must include a management program that monitors the hydrodynamics, chemical quality, and surface water–groundwater interaction [5].

The strategic character of a groundwater reservoir during periods of droughts is particularly connected to characteristics such as

- Its storage capacity and inertia in recharge processes
- Availability (it is not significantly affected in the short and medium term by a decrease in precipitations)
- Spatial distribution (occurrence in the proximity of the region to be supplied)
- Water reserves (which may be exploited in a planned manner)

Groundwater use does not entail the mining of the resource but a planned exploitation, taking into consideration environmental sustainability.

The operational procedures may be summarized in two phases:

1. Temporary exploitation of groundwater reserves, which causes their decrease and the subsequent lowering of water table and piezometric levels
2. Reserve recovery (natural or artificial recharge) after a drought, with an increase in recharge and a rise in the water table and piezometric levels

The objective of the sustainable use of water should be an integrated approach [9], taking into consideration the conjunctive use of surface water and groundwater and paying attention to both quality and quantity, based on their complementary nature.

This conjunctive use has been implemented in different ways, although it is commonly associated with the use of the surface water surplus to recharge aquifers artificially whenever precipitations make it possible and the extraction of water from the aquifers in times of drought. On other occasions, the natural, alternating use of surface water and groundwater is enough, which prevents the problems brought about by the use of artificial recharge, especially the economic ones.

A key criterion is to find a balance in groundwater use that prevents the lowering of water table and piezometric levels in the long term (exploitation) and a rise in the levels (recharge), along with the threat of waterlogging and salinization of the land.

This concept includes the use of the aquifer as a reservoir, contributing to an increase in the water regulation capacity and providing a better response to the possible drought periods. This solution is flexible due to the spatial distribution of aquifers, which entails adaptability to different situations, such as a pipeline or hydraulic infrastructure.

The conjunctive management of surface water and groundwater resources is necessary to mitigate the impact of droughts [6]. This requires a multidisciplinary approach that develops coupled models of surface water and groundwater flow in which the detailed hydrogeological characteristics (hydrodynamics and hydrochemistry) of the study area are taken into consideration. A historical series of the groundwater levels is also important for the proper calibration of the models [20].

In order to deal with the situations resulting from droughts, it is necessary to have a detailed knowledge of the following:

- Hydrogeological characteristics and estimation of the water reserves available in aquifers located near the area affected by periodical droughts
- Conditions of the aquifers to be used as regulation reservoirs
- Storage capacity of the aquifers
- Adaptation possibilities of the groundwater system for artificial water recharge

The cost should include well construction, pumping equipment, water conveyance infrastructure, monitoring systems, and system maintenance. Besides, it should include programs for the improvement of the hydrogeological knowledge, as well as the protection and management of aquifers and groundwater.

A hydrological plan considering droughts requires a good knowledge of the hydrogeology and its relationship with the related natural ecosystems, which will make it possible to overcome the problems derived from such adverse climatic conditions. An efficient system to solve these problems should implement preventive measures—that is to say that the necessary infrastructure should be available in advance—keep records, and monitor, in order to guarantee their availability if necessary.

11.5 Summary and Conclusions

Groundwater may have a strategic role in overcoming drought periods. However, there is no unique solution to mitigate the consequences of droughts. An integrated management of surface water and groundwater (conjunctive use) is required, since it is unlikely for the problem to be solved in an isolated manner. An adequate hydrological plan integrating both water sources is essential in the mitigation of the consequences of droughts.

Knowledge of the systems affected by drought situations, especially with regard to water supply and demand, makes it possible to act preventively, which constitutes an essential tool to face such conditions. This leads to securing the infrastructure that would guarantee the availability of water when needed.

As regards groundwater, it is essential to quantify the storage capacity of aquifers, as well as to assess the conditions for their incorporation into the exploitation systems, the selection of an adequate recharge system if necessary, and the monitoring and maintenance of the operations involved in the introduction of the system.

The combined use of surface water and groundwater constitutes a tool to be taken into consideration in regions subjected to periodical droughts.

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12

Reservoir Operation during Drought

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Abstract The increasing occurrence of drought events along with lack of proper drought management practices in various regions of the world has caused several socioeconomic problems for natural-resource-dependent communities. The operation of surface water resources that are quickly affected by drought, in most regions, is performed using the reservoir. Therefore, reservoir operation during drought is one of the most important drought management policies. During wet and normal periods, when inflow is sufficient, achieving reservoir operating targets does not pose a problem. However, during drought or when forecasting a drought, it may not be possible to reach the target because of an inflow shortage. To minimize the impact of drought on reservoir performance, rule curves are coupled with hedging rules to balance the shortage in water supply with the storage target. This chapter discusses reservoir operation during drought.

12.1 Introduction

One of the most important objectives for reservoir management is to control water during the wet period and allocate it during the dry period. In the case of dam construction, which has several negative environmental effects [4,8], optimal reservoir operation is necessary. Therefore, many researchers discussed on optimal operation of reservoirs [3,7]. Nowadays, the impact of climate change on the operation of reservoirs is one of the interesting areas of research [10,20]. The occurrence of extreme events is one of the effects of climate change. Thus, increasing droughts and floods is a challenge facing the water managers. What is important to supply water demand is operation of reservoirs under drought conditions.

Drought is known as the deficiency of water in one or several components of the hydrological cycle [1]. It occurs when the available water of a system is not sufficient to supply at least one of the biological, economic, and social water needs during a considerable time period [17]. Occurrence of severe and persistent droughts depletes the reservoirs' storage to critical levels, which may lead to future water supply disasters. An approach is needed for activating restrictions on allocating water to agricultural demands during a drought and predicting low flow regimes using appropriate long-lead forecasts. Hedging rules are the methods of reservoir operation during droughts, which benefit from functions of release and carryover storage at each agricultural season. Hedging rules are triggered by different levels of drought indices determined by the predicted water availability at the beginning of each agricultural season.

As proposed by Shih and ReVell [16], common drought management steps are as follows: (1) forecasting of inflows and demands; (2) consideration of drought management options; (3) establishment of levels of indicators that trigger the various options of a demand reduction program; and (4) adaptation of a management plan at the levels indicated by drought indices. Shih and ReVell [15,16] developed the continued and discrete hedging rules for a single water supply reservoir. They formulated the linear and nonlinear mixed integer programming models that minimized the maximum deficit and maximized the number of months when no water rationing is required. Chang et al. [5] developed a model to use flood-control reservoirs for drought management in the Scioto River in central Ohio. They defined different levels of drought indicators such as stream flow, precipitation, temperature, groundwater, and reservoir elevations to distinguish drought events from a normally experienced historical record. Tu et al. [18] developed multireservoir mixed integer linear programming for optimizing a large-scale regional water distribution system, taking into consideration rationing rules during droughts.

Researchers such as Vasiliadis and Karamouz [19] have dealt with demand-driven operation of reservoirs. Moreover, Karamouz and Araghinejad [12] developed a model for long-term operation of reservoirs with emphasis on drought mitigation. Researchers such as Karamouz et al. [13] and Karamouz and Araghinejad [12] have focused on the water resources systems analysis in Zayandeh-rud basin. While Karamouz et al. [13] have investigated the drought characteristics in the basin, Karamouz and Araghinejad [12] have proposed the real-time seasonal operational policies for Zayandeh-rud reservoir to mitigate drought damages.

This chapter deals with the basic methods of developing hedging rules with a demonstration of how the rules could benefit in mitigating drought loss in a case study.

12.2 Relationship between Reservoir Operation and Drought Forecasting

A step-by-step procedure for monitoring and forecasting of drought emphasizing on the role of reservoir operation is given herein. The variables and functions include all those required to forecast the occurrence probability of a drought at a specific time period, t (say, an agricultural season). The procedure is as follows:

1. Identification of stream flow forecast point(s) as well as reservoir(s) in the region
2. Implementation of the following functional relationships for the specific forecast points and the reservoir:
   - Available water (A) as a function of hydro-climatological variables of the region as well as the current storage volume of the reservoir (A)
   - Demand (D) as a function of available water at the region ($D|A$)
   - Water delivery (R) as a function of available water and water demands ($R|D \cap A$)
3. Computation of the joint probability function of A, D, and R, at the start of each time period, t. $p(A \cap D \cap R) = p(A)\, p(D|A)\, p(R|A \cap D)$ to determine the drought status as a comparison between R and D.

Obviously, deciding on the amount of release (R) results in the severity of future drought as shown in Figure 12.1.

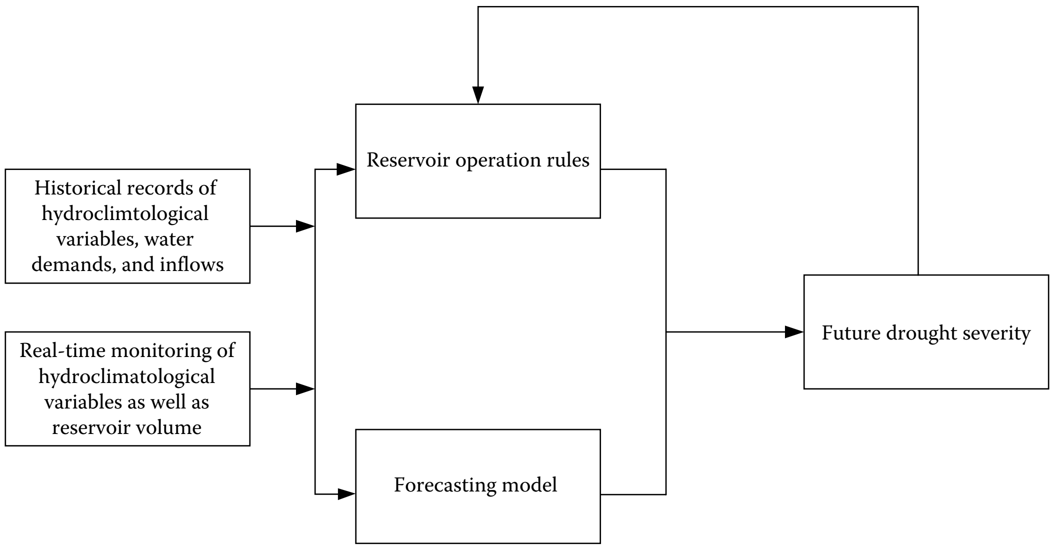

FIGURE 12.1 The role of reservoir operation in drought severity.

12.3 Reservoir Operation in Anticipation and during Drought: Hedging Rules

Reservoir operation could be based on an adaptive generation of seasonal release policies using hedging rules, where input and output data are readjusted every season based on new initial conditions of the system and predicted inflows. Operating a reservoir when anticipating and during a drought requires two major models: long-lead forecasting and optimal hedging rules. Also a range of data including hydroclimatological time series, characteristics of the system, and the drought loss information are used in different analyses of this approach.

Using a forecasting model, inflows to the reservoir are predicted. Triggers are calculated using the water currently available in the reservoir plus the expected value of future inflows to the reservoir. Restriction rules are activated upon feedback from the triggers. Optimal release and the target storage are calculated at each time step. More details are described in the following sections.

Water supply managers prefer a number of smaller shortages compared to a few very large ones, suggesting that damages are convex in the shortfalls [16]. In the general situation of actual drought, realistic reservoir management rules would suggest that during periods of incipient drought reductions be made in demand even if it can be fully delivered from storage and current inflow. This reduction prevents larger shortages in later periods of operation. The minimization of total shortfall, the objective of so-called standard operating policy, is not the objective of water managers with regard to the convexity of shortage losses during droughts [11]. To minimize the impact of current and subsequent droughts, reservoir operation rules are coupled with the hedging rules to balance the shortage with the carryover storage and to ensure that a sufficient amount of water remains in the reservoir for the following period of water supply. Decision-makers in water resources systems must evaluate the trade-offs among immediate and future use of water before the future state of supply is known. In the face of this uncertainty, forecast of future stream flow can be helpful in planning the operation. Anticipation of and during a drought, stream flow forecasts would be more valuable. The potential value of these forecasts to water resource systems operation is significant if there are modeling techniques and decision processes available to explore them [9]. Consider a single reservoir system. The continuity equation for the reservoir can be written as follows:

$$S_t + I_t - R_t - E_t = S_{t+1} \tag{12.1}$$

where
S_t is the beginning storage during time period t
S_{t+1} is the ending storage during time period t
I_t is the inflow during time period t
E_t is the total loss during time period t
R_t is the release during time period t

Storage, S_t, plus forecast inflow, I_t, are common variables for a drought index in hedging rules. During operation of the reservoir, hedging rules are activated, when drought indices, say $S_t + I_t$, get to specific values called drought triggers. In general, during each time period t, the relationships between the drought triggers and linear two-point hedging rules, as shown in Figure 12.2, are represented by one of the following equations:

$$\text{If } S_t + I_t < \text{Trigger}_{1t} \quad \text{then } R_t = I_t + S_t \tag{12.2}$$

$$\text{If } \text{Trigger}_{1t} \le S_t + I_t < \text{Trigger}_{2t} \quad \text{then } R_t = D_t \tag{12.3}$$

$$\text{If } \text{Trigger}_{3t} \le S_t + I_t \quad \text{then } R_t > D_t \tag{12.4}$$

where
Trigger_{it} is the specific value of $S_t + I_t$ representing drought triggers (i = 1, 2, 3)
D_t is the water demand during each time period t

Drought triggers in a reservoir-operating system depend on both hydrology of the system through prediction of forecast inflow (I_t), and economic benefits of operation, through evaluation of trade-offs

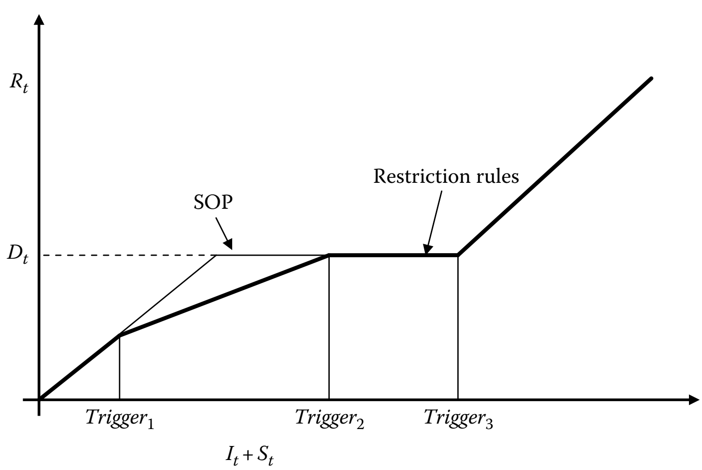

FIGURE 12.2 Two-point reservoir operation hedging rule.

among immediate and future uses of water. Hedging rules converge to the well-known standard operating policy (SOP) as shown in Figure 12.1, in the absence of enough knowledge of hydrologic or economic characteristics of a system [14]. The problem in setting up a hedging rule for a water resources system is to calculate drought triggers (Trigger_{it}).

Draper and Lund [6] presented an analytical method for the derivation of triggers in a hedging-rule-based operating policy. They showed that a hedging rule is optimal when the sum of economic value of release and storage is maximized:

$$\begin{aligned} &\max\ B(R)+C(S) \\ &S+I=A \\ &S<\text{Cap} \\ &S>0 \\ &R>0 \end{aligned} \tag{12.5}$$

where

$B(R)$ represents current water delivery benefits

$C(S)$ represents expected value of future economic benefits from keeping water in the reservoir

Equation 12.5 should be considered along with the water balance equation (Equation 12.1) as well as active and dead storage volume constraints. Draper and Lund [6] solved this problem analytically for benefit and storage functions of different orders. They showed that in the case of quadratic benefit and storage value functions where $B(R)=a_r+b_rR+c_rR^2$ and $C(S)=a_s+b_sS+c_sS^2$, the drought triggers are calculated as follows:

$$\text{Trigger}_{1t}=\frac{b_s-b_r}{2c_r} \tag{12.6}$$

$$\text{Trigger}_{2t}=\min\left[D_t\left(1+\frac{c_r}{c_s}\right)+\frac{b_r-b_s}{2c_s},\ \text{CAP}\left(1+\frac{c_s}{c_r}\right)+\frac{b_s-b_r}{2c_r}\right] \tag{12.7}$$

$$\text{Trigger}_{3t}=D_t+\text{CAP} \tag{12.8}$$

where

D is the water demand

CAP is the maximum capacity of reservoir

Also in case that I_t+S_t are less than Trigger_{2t} and more than Trigger_{1t}, the optimum release is calculated as

$$R^*=\frac{b_s-b_r+2c_s\left(S_t+I_t\right)}{2\left(c_s+c_r\right)} \tag{12.9}$$

These equations give a two-point linear hedging rule as shown in Figure 12.1. Whenever the release benefit functions and the optimal carryover storage value function are available, optimal hedging rules can be derived by Equations 12.6 through 12.9. During a real-time operation of reservoirs, three factors control the optimum releases that result from the hedging rules. The factors predicted are available water, estimated water demand, and storage/release benefit functions.

12.4 Case Study

An example of using the proposed method is presented for the Zayandeh-rud River basin, which is located at the central part of Iran (Figure 12.3). The water resources of Zayandeh-rud are dependent on the Zayandeh-rud reservoir. The hydrologic situation of the Zayandeh-rud basin is generally indicated by the inflow to the Zayandeh-rud reservoir. The average annual inflow to this reservoir is about 1600 million cubic meters (Mm^3) with the standard deviation of 425 Mm^3. The climate of the basin may be influenced by the large-scale climate signal of *El Nino* Southern Oscillation (ENSO) as demonstrated by Araghinejad et al. [2]. ENSO could be considered as a predictor of seasonal to annual inflow to the Zayandeh-rud reservoir. The average annual agricultural water demand in the basin supplied by the surface reservoir is 1088 Mm^3 with the standard deviation of 73 Mm^3. There are also 416 Mm^3 annual demands for domestic and industrial consumption of the basin. During droughts, the restriction on water reservoir allocation is considered only for the agricultural demands. Table 12.1 shows characteristics of Zayandeh-rud reservoir.

To conserve water and to minimize the impact of a severe drought in the future, the reservoir must be operated under certain restrictions. There are some policies dictated by local and federal authorities that define the objectives of strategic operation of the Zayandeh-rud reservoir. The priority of domestic and industrial water allocation is the highest among the water users, so allocation of these demands is mandatory in every situation as well as the allocation of minimum instream flow. The domestic and industrial water demand from October to March (first agricultural season) is 126,106 m^3 and it is equal to 324,106 m^3 from April to September (second agricultural season).

Maximum benefit is obtained when all agricultural water demands are allocated. Based on the damages incurred during the recent droughts in the basin, the release value functions of the first and

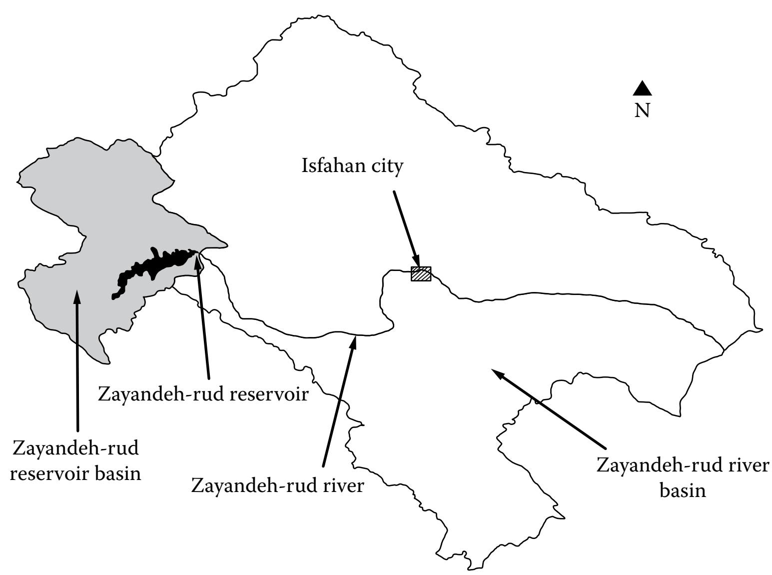

FIGURE 12.3 The map of Zayendeh-rud basin and the location of Zayendeh-rud reservoir.

TABLE 12.1 Characteristics of Zayandeh-rud Reservoir

Maximum Storage (Mm^3)	Minimum Storage (Mm^3)	Average Annual Inflow (Mm^3)	Standard Deviation Inflow (Mm^3)
1470	380	1600	425

the second agricultural seasons are estimated [12]. The release value functions are represented by quadratic functions of

$$B_1(R) = -0.759R^2 + 419.5R \quad (12.10)$$

and

$$B_2(R) = -1.88R^2 + 2603.5R \quad (12.11)$$

for the first and second seasons, respectively. The storage value of the first and second seasons is presented as follows:

$$C_1(S) = -0.424S^2 + 1005.5S \quad (12.12)$$

$$C_2(S) = -0.703S^2 + 1831.6S \quad (12.13)$$

The drought damages and the release benefit functions of Zayandeh-rud reservoir are shown in Figure 12.4.

Figure 12.5 shows the variation of actual reservoir storage and simulated reservoir storage using the hedging rules (HR) equations (Equations 12.6 through 12.9) in real-time operation of the reservoir during the period

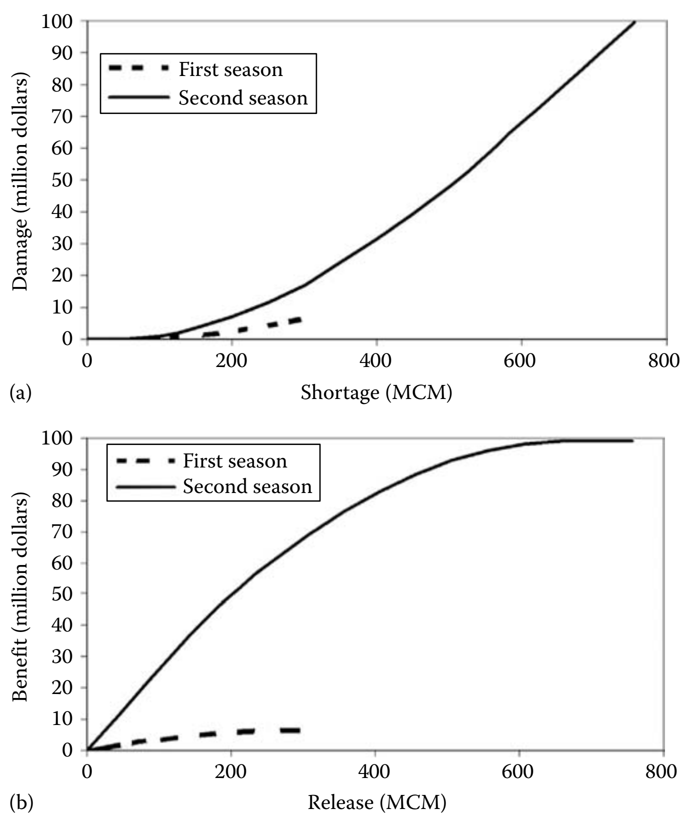

FIGURE 12.4 (a) Drought damages and (b) release value functions of first and second agricultural season.

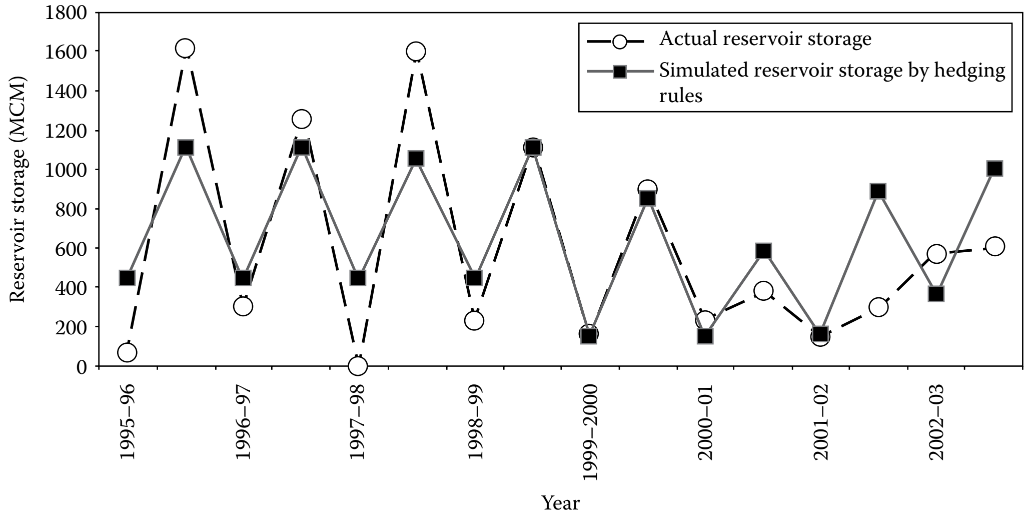

FIGURE 12.5 Actual and simulated reservoir storage during the period of 1995–1996 to 2000–2003.

of 1995–2003, when the system had experienced a record drought. The model uses the same constraints that existed in the real-world operation of the reservoir. The performance of HR has reduced the recent drought damage by 80% to $9.68 million. The hedging rules results presented in Figure 12.4 do not consider the short-term operation of the reservoir, so this reduction is not expected in a real-world operation; however, it is emphasized that the use of the proposed approach could significantly reduce drought damages.

12.5 Summary and Conclusions

The approach uses long-lead forecasts as well as hedging rules to activate specific restrictions on agricultural demand allocation during and when anticipating a drought. This approach is suitable for considering the climatic information in the reservoir operation. The major contribution of the proposed algorithm is to integrate various components such as inflow forecasts, release value function, and reservoir characteristics to provide a reliable decision tool. The results indicate that operating schedules from the proposed approach, which considering the aspect of drought mitigation, are significantly different from those obtained by a model that does not consider this issue. In the simulation scenarios, comparing the proposed approach with the actual operation of the Zayandeh-rud reservoir, the effectiveness of the approach was demonstrated by decreased drought damage by a factor of 80%.

From the standpoint of water resources decision-making, the hedging rules approach has a potential to incorporate the hydro-climatological state of the basin into water-resources-related decisions. This is especially valuable when there is a strong relationship between predictors and climate variability in a basin. The proposed approach can be easily improved to also incorporate short-term operation. Depending on the long-term decision, it is possible to use short-term tactics to decide on optimal water release and conservation schemes in real-time operation. This approach can also be generalized to a wider class of reservoir management problems such as multipurpose multireservoir systems with varying water demands.

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13

Crisis Management Planning and Drought Management Plans

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Abstract Drought management plans (DMPs) are regulatory instruments that establish priorities among the different water uses and define more stringent constraints on access to publicly provided water during droughts, especially for nonpriority uses such as agriculture. Crisis management planning (CMP) refers to the methodology used by executives to respond to and manage a crisis and is an integral part of a business resumption plan. This chapter provides a general overview of drought and DMP and discusses the differences between DMP and CMP.

13.1 Introduction

Drought is a major problem for water management and environmental protection [13]. Drought conditions have spread around the world, including North Africa, the Middle East, West Asian countries, India, China, and North Central and South America [21]. This phenomenon directly affects more people than any other natural disaster and in this respect is ranked first. Although drought in terms of physical destruction is not like most natural disasters, it can reduce water supplies, affect wide areas, and create a wide range of economic, environmental, and social impacts [2,16].

The lack of a precise and universal definition of "drought" is causing confusion for some decision-makers because scientists may take issue with the existence of drought conditions and their severity [30].

The long-term impacts of prolonged drought are profound, and we cannot prevent it; but measures can be taken to prepare us to cope with drought, to develop a flexible ecosystem with a high ability to recover from drought, and to mitigate the impacts and effects of drought [24]. Usually, the response to this natural hazard is reactive (measures are taken after drought occurrence) rather than proactive (mitigation measures are taken as part of drought preparedness) [33]. This approach and stop-gap measures are largely ineffective in mitigating the impacts of drought [37,30]. It is therefore essential to establish and develop a drought management plan (DMP) to minimize the impacts. Historically, more attention has been given to flood management than drought management [29]. Basically, the purpose of a DMP is to reduce the drought risk and its impacts [34]. This chapter provides a general overview of drought and DMP and discusses the differences between DMP and crisis management planning (CMP).

13.2 Types of Drought

The most commonly used drought definitions are based on meteorological, agricultural, hydrological, and socioeconomic droughts [18].

13.2.1 Meteorological Drought

Meteorological drought is the result of the occurrence of continuous large-scale disruptions in the global circulation pattern of the atmosphere [29]. This drought is commonly understood to mean a degree of dryness (in comparison with some "normal" or average amount) and a certain duration of that dry period. Another definition of meteorological drought refers to a situation when there is a significant decrease from normal precipitation over a region (i.e., more than 10%) [21]. Definitions of this type of drought must be considered as region specific because the atmospheric conditions that are related to precipitation are highly variable from region to region [31]. Empirical studies have shown that the meteorological drought is not the result of a single cause but the result of many, which are often synergistic in nature [13].

13.2.2 Agricultural Drought

Agricultural drought occurs when soil moisture and rainfall are insufficient to support the needs of a particular crop during growth [21,26]. This type of drought connects the various characteristics of meteorological (or hydrological) drought to agricultural impacts and concentrates on precipitation deficiency, differences between the actual and potential evapotranspiration, the lack of soil water, the reduced water supply levels, and so on. Agricultural drought can affect crop production; in other words, the deficient topsoil moisture at planting may hinder germination, resulting in a reduction of the final yield [31].

13.2.3 Hydrological Drought

Hydrological drought is brought about when periods or amounts of precipitation (including snowfall) fall short and affect the hydrological system, such as the surface or subsurface water supply and soil moisture [31]. The deficiency of rainfall, especially during the winter and early spring when evapotranspiration is low and groundwater resources are typically recharging, in hydrological conditions can result in low streamflows [26]. Hydrological drought does not occur only when there is a deficiency of precipitation; rather it could occur even when the rainfall is normal, but when accompanied by a substantial reduction in surface water holding capacity [21,36]. These droughts tend to show up more slowly and are usually out of phase with or delay the occurrence of meteorological and agricultural droughts [31]. The frequency and severity of the hydrological drought are often studied on a watershed or river basin scale [12].

There is a time lag between the lack of precipitation and the decreased water levels in water resources such as streams, rivers, lakes, and reservoirs; therefore, hydrological measurements are not the first indicators of a drought condition [13].

13.2.4 Socioeconomic Drought

When the demand for goods or services exceeds the available supply as a result of precipitation deficiency, socioeconomic drought occurs [26]. Demand and supply must converge but if they do not, vulnerability and the incidence of drought may increase [31]. Population increase can substantially alter the demand for these economic goods over time [36].

Although factors such as high winds, high temperatures, and low relative humidity may intensify the drought's severity, all types of drought are caused by a deficiency of precipitation [31]. Meteorological drought is defined initially in terms of natural characteristics. However, agricultural, hydrological, and socioeconomic droughts place a greater emphasis on human or social aspects of drought and natural resources [36].

13.3 Effects and Impacts of Drought

The economic, social, and environmental impacts of droughts have increased significantly in recent decades and in many regions of the world [36,37]. Patterns and trends show that the effects of drought will eventually affect the availability of water resources and thus have an impact on water ecosystems [13]. Drought impacts are numerous. These phenomena can prevent populations from accessing a minimum water supply, reduce crop yields, and affect environmental ecosystems or increase the pressure among users [12]. There is intense competition between the economic, environmental, and social values for scarce water resource [34]. The impacts of drought are also largely nonstructural, spatially extensive, and not as visual as other natural hazards, hence making it difficult to assess the effects of drought and respond in a timely and effective manner and hard for the media to communicate the significance of the event and its impacts to the public [30]. Drought can affect vast areas and cause a wide range of economic, environmental, and social impacts, although it is not as physically destructive as most natural disasters [16,29].

Drought becomes an emergency or disaster by its impact on local communities and the environment, but by itself it does not trigger an emergency. In fact, this depends on the vulnerability of people and the environment to a drought disaster [36].

13.3.1 Social Aspects

The large adverse consequences of drought events are the impacts on the socioeconomic conditions of people living in drought-prone areas via their affect on water supplies and their quality, agricultural and energy production, and ecosystem health [3]. The social impacts typically include public safety, health, a struggle between water users, a reduced quality of life, and injustice in the distribution of impacts and disaster relief [27].

13.3.2 Economical Aspects

Economic impacts include the effects of drought on people's living expenses or business matters. For example:

1. Farmers may lose money if a drought destroys their crops or their farms.
2. If a farmer's water supply is too low, the farmer may be forced to spend more money on irrigation or to find new water supplies.
3. Reduced water supply may impair navigability, so that other transportation costs are increased [27].
4. If drought dries up most water supplies that are used to produce hydropower, power companies that rely on this type of power may be forced to spend more money on other fuel sources. Consequently, companies' customers end up paying more money.

5. Water companies may be forced to spend money on new or additional water supplies.
6. Food prices may rise.

13.3.3 Environmental Aspects

Droughts have adverse consequences for the environment. The environmental impacts of drought include forest/range fires, soil erosion, direct damage to plant and animal species, loss of wildlife habitat (wetlands, lakes, and vegetation) and biodiversity, reduced air and water quality, mortality of fish species, loss of biodiversity in terrestrial areas depending on the aquatic system, impacts on wetlands, forest fire risk, and ecological status [8,13,27].

13.3.3.1 Agriculture

Agriculture consumes most freshwater compared to other sectors [22]. So the greatest impacts of drought are usually experienced in the agricultural segment. Agricultural drought is frequently associated with increases in insect infestations, plant disease, and wind erosion [27]. These effects may lead to economic impacts of drought in agriculture:

1. A reduction in agriculture employment
2. A decline in farmland prices
3. Reduced revenues
4. An increase in the prices of food products
5. Threats to public health
6. The destruction of villages

13.3.3.2 Hydrological Aspects

Droughts produce negative direct impacts on the available water resources [12]. Its impacts on surface waters are generally more evident than the impacts on groundwater, both directly and indirectly, but not necessarily less damaging [13]. In fact, groundwater resources are the last water supply to be significantly affected by a drought event. However, prolonged drought can lead to hardship in cities, farms, and to other users who are reliant upon groundwater for their water supply [27]. Also drought, especially prolonged drought, has a much greater impact on smaller water resources, which thus experience significant fluctuations during dry conditions [27]. Water in hydrologic storage systems is often used for multiple and competing purposes such as flood control, irrigation, fire protection, recreation, navigation, hydropower, and wildlife habitat [31], so hydrological drought can affect these sectors.

13.3.3.3 Water Quality

Drought can have an impact on both the availability of water and the quality of water. Low water levels in water supplies can result in quality problems, which include

1. Increasing the water temperature
2. Increasing the nutrient levels and salinity of water
3. Decreasing the oxygen levels
4. Bacteria problems in water distribution systems [9,15,19]

13.3.3.4 Other Impacts

Other drought impacts occur in soil characteristics (including soil erosion), water management practices in catchment areas, transportation, recreation and tourism, and the energy sector. They may also endanger the survival of animal and plant species, aggravate losses in crop and livestock production, increase the incidence and severity of forest fires and wildfires, decrease surface and groundwater supplies, and increase demands for energy in response to searing heat [3,21,34].

13.4 Drought Management Plans

Experience has proven that prevention is better than cure; accordingly, the annual cost of drought reduction programs is far less than the annualized cost of post-disaster measures for restoration and rehabilitation [6]. A DMP can be useful and is the efficient tool for managing water resources in drought conditions. The DMP is a regulatory instrument that establishes the effective operating procedures to manage water demand, to determine the priorities among water users, to define more accurate constraints to access water during periods of drought, and to assess the options of water supply before, during, and after drought-related water shortages [14,23].

Governments need the capacity and expertise to respond in a timely and effective way to drought across various communities, especially those with poor resources [6]. A DMP has become a government's main tool to promote their response to droughts [34]. Nowadays, a large numbers of countries have found the potential benefits of drought planning [29].

A DMP should have an integrated approach for the effective implementation of drought management that includes reducing the risk of drought and a reaction to drought and relief [5]. DMPs should be established or developed before they are needed [13]. Unfortunately, drought management has followed the traditional approach, which is largely based on crisis management [30].

13.4.1 Basis and Content of a Drought Management Plan

The goal of a DMP is to promote dialogue between water users and those who are dependent on water resources [24] and also to maximize efficient utilities and to achieve the greatest public profit from limited water resources to protect public health and safety (domestic water use, sanitation, water quality, etc.) and the environment (e.g., fire protection) while providing water to all consumers in a fair and equal way [14]. In DMP, protecting the health of citizens and aquatic environments is important, but not sufficient, so sustaining economic and social activities should also be considered [25]. A DMP should explain how the available water should be allocated among the different water uses during times of droughts [23].

The drought plan is not a static document or a discrete event. It should be a dynamic framework for an ongoing set of actions to prepare for, and effectively respond to, drought, including periodic reviews of the outcomes and priorities; readjustment of goals, means, and resources; strengthening institutional arrangements, planning, and policy-making mechanisms for drought mitigation and responses [13,34]. The successes and failures of the policies and plans should be evaluated continuously and appropriate modifications should be made, if necessary [36].

A DMP is the program of measures, which includes the procedures for impact assessment, proactive risk management actions, and preparedness plans to increase coping capacity and effective crisis management to reduce drought impacts [37]. An effective DMP needs to balance prevention, mitigation, preparedness, response, recovery, and disaster-related development [6]. These different types of measures can be applied in each region when it has drought status [12]. In brief, an important aspect of a DMP is to define the severity of drought and the actions to be taken with appropriate levels of response [12,19]. A good plan includes three major components: mitigation, response, and vulnerability assessment [6]. But in some resources, monitoring is mentioned as a fourth component [7,25].

The 10 steps for the drought planning process are set out in Table 13.1.

1. The appointment of a drought task force is the first stage of the DMP process. The purposes of this step are
    a. To supervise and coordinate the development of the plan before drought occurrence.
    b. To coordinate actions, implement mitigation and response programs during the times of drought, and make policy recommendations to the relevant government officials.
2. The second step defines the goals of a risk-based national DMP. In this step, government officials should consider many questions as they define the purpose of the plan, including the purpose and role of government in drought mitigation actions, the most vulnerable sectors of economic and social

TABLE 13.1 Ten-Step Planning Process

1.	Appoint a drought task force or committee
2.	State the purpose and objectives of the drought mitigation plan
3.	Seek stakeholder input and resolve conflicts
4.	Inventory resources and identify groups at risk
5.	Prepare and write the drought mitigation plan
6.	Identify research needs and fill institutional gaps
7.	Integrate science and policy
8.	Publicize the drought mitigation plan, build awareness and consensus
9.	Develop education programs
10.	Evaluate and revise drought mitigation plans

Source: Wilhite, D.A. et al., *The Basics of Drought Planning: A 10-Step Process*, National Drought Mitigation Center, Lincoln, NE, 2001.

drought impacts, the historical impacts of drought and the associated responses, the scope of the plan, the legal and social implications of the plan, and the environmental effects caused by drought.

3. In the third step, it is necessary to identify all the citizen groups that have a stake in drought planning (stakeholders) and to understand their interests. For fair representation and effective drought management and planning, these groups must be involved early and continuously.
4. An inventory of natural, biological, and human resources, including the identification of constraints that may hinder the planning process, may need to be initiated by the commission. The objective of step 4 is to identify the constraints to the planning process and to the activation of the plan in response to a drought condition (constraints may be physical, financial, legal, or political).
5. The purpose of step 5 is to provide a drought preparedness and mitigation plan that was described in detail in Section 13.5.
6. The commission for drought should collect a list of needs and deficiencies and make the recommendations to the government on remedial measures to be taken.
7. The purpose of step 6 in the planning process is to integrate the science and policy of drought management. The drought commission should consider the various alternatives to bring the science and policy together and maintain a strong working relationship.
8. To communicate constantly with the public, emphasizing how the plan decreases the impacts of drought in both the short and long term and showing the reaction of people to the response for different degrees of drought.
9. An education program to increase awareness of short- and long-term water supply issues will enable people to respond to drought when it occurs and ensure that drought planning does not lose ground during nondrought years.
10. The final step in the planning process emphasizes revising the plan to keep it current and making a post-drought evaluation of the plan's effectiveness [4,28,30,35].

13.4.2 Drought Management Plan Objectives

Drought plan objectives should be diverse and unique for each region and reflect the physical, environmental, socioeconomic, and political characteristics of the region [34].

The general objectives of the DMP include

1. Developing a system of information management, and monitoring and evaluating the drought situations to detect and monitor the type and severity of the situations
2. Compiling the drought indices maps
3. Implementing and prompting the early warning systems
4. Establishing and taking the appropriate action for risk reduction, including preparedness, mitigation, response, recovery, and rehabilitation [6,25].

The specific objectives of the DMP include

1. Making sure that there is water for sustaining the life and health of the population.
2. Minimizing negative drought effects on environmental water flows and public water supplies.
3. Minimizing the negative effects on economic activities, according to the prioritization of uses that are based on water polices [11,12].

13.5 Risk Management

The consequences of the exposure to drought hazard (i.e., probability of occurrence) and societal vulnerability are represented by a combination of economic, environmental, and social factors. It is essential to identify the most significant impacts and assess their underlying causes in order to reduce vulnerability to drought [34]. Risk management, and therefore risk reduction, is the core principle of a DMP and the main aim is to reduce the vulnerability of farming communities [6]. Preparedness, mitigation, and prediction are the most important items of risk management, along with early warning activities initiated before the drought with the goal of reducing the impacts associated with the subsequent events [34].

Blaikie et al. (1994) [1] originally propounded the risk as the sum of the hazard and vulnerability (risk = hazard + vulnerability). Recently, a risk has been considered as the product of the hazard and vulnerability (risk = hazard × vulnerability). Hazard in these models represents the probability of occurrence or frequency of droughts; vulnerability represents the most extensive concept of biophysical and social vulnerability in a region. Due to the multiplication relationship, the drought risk for a location is zero if there is no chance of the hazard or there is no vulnerability. There are very few places, if any, around the world where the probability of drought is zero. However, this may not be true for other natural hazards [16].

Vulnerability, on the other hand, can be defined by social factors such as land use patterns, population, government policies, social behavior, water use, economic development, variety of economic base, and cultural composition [34].

Risk management that includes mitigation, prediction, or early warning actions could reduce future impacts, lessen the need for government intervention in the future, focus on identifying where vulnerabilities exist (particular sectors, regions, communities, or population groups), and address these risks through systematically implementing mitigation and adaptation measures that will lessen the risk associated with future drought events, though historically little attention has been given to this. Because of this emphasis on crisis management, society has generally moved from one disaster to another with only a low risk reduction [30,37]. The crisis management approach has been ineffective (i.e., assistance was poorly targeted to specific impacts or population groups), poorly coordinated, and untimely; more importantly, it has done little to reduce the risks associated with drought and, for the most part, previous responses to drought in all parts of the world have been reactive [30].

Since climate change amplifies the frequency and severity of droughts in a region, there is an urgent need to develop better drought monitoring and management systems [3]. The importance of information on the impacts of droughts and their causes is for reducing risk in advance of the actual event and for making appropriate responses during the drought [2,34]. In fact, there must be an understanding as to which people and sectors may be most affected by drought, why these impacts occur, and if these relationships are changing over time [16].

One of the paradigms that helps to improve drought management is the encouraging of preparedness and mitigation through the application of the principles of risk management [30].

13.5.1 Drought Mitigation and Preparedness

Risk-based drought management planning includes drought mitigation and preparedness, which can reduce the impacts of drought [29].

Preparedness includes pre-event activities that are designed to enhance the level of readiness or promote operational and institutional capabilities for responding to drought events. The goal of the preparedness planning process is to change significantly the way we prepare for and respond to drought by placing greater emphasis on risk management and the adoption of suitable mitigation proceedings [36]. Risk management can be promoted by developing preparedness plans at various levels of government, adopting mitigation actions and programs, creating a safety net of emergency response programs that ensure timely and targeted relief, and providing an organizational structure that enhances coordination within and between the levels of government and with stakeholders [37].

Mitigation is outlined as short- and long-term actions, programs, or policies implemented throughout the period of drought that reduce the degree of risk to human life, property, and productive capacity [34]. Hazard mitigation refers to the reduction or elimination of the long-term risk to people and property from hazards and their effects [18]. Four basic components of drought mitigation are awareness, avoidance, early warning, and rehabilitation [6]. In the DMP subject, there are different groups of mitigation measures: the first group is structural measures (new pumping wells, new pipes, use of new desalination plants, etc.) and the second group is nonstructural measures (changing the priority of the users, water savings and demand reductions, increase in the use of groundwater, etc.). For example, the conjunctive use of surface and groundwater is one of these measures [10].

Mitigation strategies that are developed for multiple hazards, including droughts, may be the most cost-effective and successful in reducing the losses caused by droughts and other hazards in the future [16]. The crucial part of drought management is emergency response because it is improbable that the government and others will predict, avoid, or reduce all potential impacts through mitigation programs [21]. Governments are beginning to identify the need for enhanced mitigation actions to lessen the increasing economic, environmental, and social impacts of droughts. Unfortunately, most drought plans still give the importance to emergency response rather than mitigation [16].

The development and dissemination of information are the first step in drought mitigation by political decision-makers, administrative officials, and, most importantly, individuals vulnerable to drought [6]. For making fair and effective decisions on short- and long-term mitigation actions, a clear understanding of the type of hazard, its potential impacts, causal factors, and temporal trends is critical [16].

All mitigation measures are not appropriate in all cases [37]. The use of all components of the cycle of disaster management (Figure 13.1) for mitigating the effects of drought in comparison with using only the crisis management portion of this cycle is important [30]. Identifying the necessary mitigation actions is not sufficient for risk management. Mechanisms must also be put into place to ensure that they are done [16].

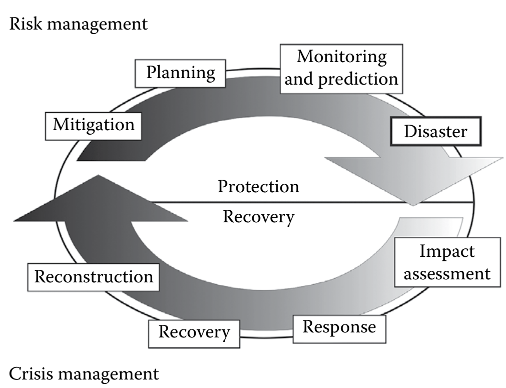

FIGURE 13.1 Cycle of disaster management. (From Wilhite, D.A. et al., *The Basics of Drought Planning: A 10-Step Process*, National Drought Mitigation Center, Lincoln, NE, 2001.)

Indicator	1–0.5	0.5–0.4	0.4–0.3	0.3–0.2	0.2–0.15	0.15–0.1	0.1–0
Status	Normal	Pre-alert		Alert		Emergency	
Objective	Planning	Information-control		Conservation		Restrictions	
Type of measure	Strategic			Tactics		Emergency	

FIGURE 13.2 Type of mitigating measures according to the established threshold. (From Estrela, T. and Vargas, E., *Water Resour. Manag.*, 26(6), 1537, 2012.)

The following recommendations are provided to enhance drought preparedness and mitigation:

1. Because of drought, policy plays an important role in drought management and should be developed and promoted regularly.
2. Implementation of preparedness and mitigation strategies should be upgraded at all levels of the community and on farms.
3. Promote various species of vegetation.
4. Long-term and medium-term measures should be considered in drought preparedness and mitigation.
5. Linking the drought relief and drought plans at local and national levels.
6. Improving the efficient water management for irrigated, rainfed, and mixed systems.
7. Managing the conjunctive use of ground/surface water and reuse water resources for irrigation, industrial, and urban water supplies.
8. Emphasizing water use optimization in lieu of yield maximization.
9. Improving the integrated approach to drought preparedness and mitigation.
10. Most vulnerable areas should be identified.
11. Consider effective communication [10,24].

To achieve the purposes of a drought management plan, DMPs should adapt to the different established drought phases and describe the measures that should be applied in that status. When the drought progresses and a more critical situation arises, measures go from control and information to conservation and restriction types [11,12] (Figure 13.2).

13.6 Moving from Crisis to Risk Management

Moving from crisis to risk management in drought management is difficult because little has been done to understand and address the risks associated with drought and very little institutional capacity exists in most countries for altering this paradigm, so many of the ideas concern the domination of short-term emergency response or crisis management, rather than long-term mitigation or risk management [30,31]. Because of the ineffectiveness of the crisis management approach, greater interest has evolved in recent years in the adoption of a more proactive risk-based management approach in some countries, though the analysis of drought management policies indicates that often decision-makers react to drought events mainly through a crisis-management method, rather than on developing comprehensive, long-term drought preparedness policies and plans [13,30]. Movement from crisis to risk management certainly needs a paradigm shift [29]. In the disaster management cycle (Figure 13.1), risk management favorably complements crisis management, such that in time one would expect the magnitude of impacts (whether economic, social, or environmental) to lessen [30].

13.7 Crisis Management Planning

When focusing on events that occur simultaneously with the public awareness that time is limited for an effective response, such events represent a time of crisis. In fact, the word "crisis" is taken from the Greek "*krisis*," which means "decision." In the Merriam-Webster dictionary there are the following definitions of crisis: a decisive moment (as in a literary play); an unstable or crucial time or state of affairs in which a decisive change is impending [30].

Drought should not be considered as a crisis of an urgent nature but as a management problem [20]. Drought effects and impacts are substantial, and governments have addressed the drought primarily through the crisis management approach [30].

CMP, which is a part of DMP, is an actionable program, which is applied in a time of crisis to minimize damages to all sectors of the community [20]. Drought crisis management is a systemic and complex process, and is multidimensional, like the drought itself [17]. Crisis management is the first approach that a government takes to cope with drought. This type of management approach has been followed in both developed and developing countries [30]. It needs to be used less if it is to be consistent with the long-term DMP [21].

The goal of drought crisis management is to facilitate the management of the crisis situation to avoid or minimize the negative impacts on the community at large [20]. A CMP should be flexible, include ecological, economical, social, and cultural knowledge, and be a program based on low operational levels [17].

Crisis is related to decision-making [30]. For the implementation of a DMP, it is necessary to have a crisis management group to deal with the various phases of the drought. One of the tasks of this group is the management of new and unforeseen crisis situations that may occur. In fact, care must be taken regarding all aspects of crisis management [20].

Drought crisis management should involve strategic planning and operational schematization for long- and short-term droughts, which occur in a county, region, and even global areas [17].

A continuous and integrated multidisciplinary process of planning and implementing measures of disaster management should be aimed at

- Minimizing the risk of disasters
- Mitigating the disaster severity or its consequences
- Instilling an emergency situation and preparedness
- Responding in a timely and effective way to disasters [6]

For a long time, the crisis management approach has existed in response to drought and is ingrained in our culture and reflected in our bodies. This management can cause low self-reliance and high dependency on governments and donors [29]. However, a crisis can act as a catalyst for change and political consent even while crisis management itself is not usually an effective approach in the long term [30].

13.8 Summary and Conclusions

For a long time, the crisis management approach has existed for responding to drought. But crisis management leads to stopgap measures that are costly and ineffective at mitigating the impacts of drought. If governments and nations want to reduce significantly the impacts of drought, they must establish a DMP. This is a program of measures that should include three major components: mitigation, response, and vulnerability assessment. An effective DMP can remove the "crisis" from actions taken to respond to drought and reduce the problems caused by water scarcity. A CMP is an important part of DMP, but it should be only one part of a risk management strategy. Governments should provide a framework for action and coordination that is flexible and responsive to the various situations in a drought condition. DMPs should be evaluated regularly. There are two modes of evaluation to increase the effectiveness of a drought plan: ongoing evaluation and post-drought evaluation.

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14

Functional Analysis of Regional Drought Management

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Abstract Droughts are regional in nature and, unlike other water hazards, their impacts don't have precise borders. Regional characteristics of a drought, such as covered area, total water deficit, or return time, are very important in determining the phenomenon's severity and thereafter for setting a regional drought management plan (DMP). There are some major challenges in the debate about regional drought research—challenges that stress the importance of developing a comprehensive understanding of the climatology of drought and determining the features of these events at regional level. A clear understanding of droughts and their behavior will improve the resilience of the affected regions and their capacity to recover after such events. A DMP should be prepared in advance, based on relevant country-specific legislation and careful studies concerning the characteristics of the drought in the region, its effect, and possible mitigation measures. Regional drought policies and plans should specify the respective roles of different regional stakeholders and available resources that will be required to implement appropriate drought risk reduction activities. This chapter attempts to realize a functional analysis of regional drought management by gathering the disperse information on this topic and identifying knowledge gaps and future research directions.

14.1 Introduction

Due to the complexity of the phenomenon, the existing definitions of drought have been stated and addressed according to the respective field. It is generally accepted that droughts originate from a deficiency of precipitation, which results in water shortage for a particular activity or for a specific target group. The definition of drought should contain at least four elements [14]:

1. Nature of considered water scarcity
2. Considered period
3. Truncation level
4. Regional aspects

It is this last element that makes it almost impossible to find a universally accepted definition for drought. Palmer [47] brings into question the definition of some key terms related to drought. Thus, he defines drought as a meteorological phenomenon characterized by a prolonged and abnormal deficiency of moisture for a specific period or a longer time from several months to even years, during which the supply of moisture at a specified climatological time falls below expectations. At a very general level of discussion, drought is a temporary recurrent phenomenon characterized by a reduction of rainfall in a given area (regional aspect).

The fact that drought is a recurrent phenomenon means that it is a component of the climate cycle, and thus the discussion is about a normal phenomenon and not an extraordinary event. Rossi [54] also defines drought as a recurring natural phenomenon associated with a lack of available water resources in a large geographical area and extended over a significant period of time. The severity and intensity of drought can "push" this phenomenon, because of its impact, out of the "normal" events area.

How can we define "normal"? This is a very common term in climatology, with constant references made to deviations from normal. In analyzing a phenomenon such as drought or any other, it is very important to work with data sets of relevant size in order to have accuracy. It is therefore suggested to use "averages" instead of the term "normal" as these would provide values closer to reality.

In most cases, meteorological drought is defined on a regional basis and varies according to regional climate characteristics. Therefore, it is almost impossible to extrapolate a definition from one region to another.

According to Takeuchi [73], drought is a situation that is encountered each time that forecasted water quantities that are planned to be used cannot be provided due to different reasons. In 1982, McMahon and Arenas [39] considered drought as a period of dry weather long enough to cause hydrological imbalances with connotations of humidity deficit depending on the water use by people.

Warwick [87] defines drought as a condition of humidity deficit enough to have adverse effects on vegetation, animals, and humans in a considerable area.

A definition of the phenomenon in very general terms is given by Beran and Rodier [3]: The main characteristic of a drought is a decrease in the availability of water resources during a given period and in a given area (regional aspect). The World Meteorological Organization [91] defines drought as a prolonged and extended deficiency of precipitations, mentioning that drought is a regional phenomenon and its characteristics differ from one climate regime to another (regional aspect). In *Encyclopedia of Weather and Climate*, Schneider [60] defines drought as an extended period—a season, a year, or several years—with reduced precipitation in relation to multiannual statistics for the respective area (regional aspect). Chang and Wallace [9] emphasize the distinction between a heat wave and a drought, noting that the typical temporal scale associated with a heat wave is on the order of weeks while droughts can persist for several years. The combination of a heat wave and a drought has socioeconomic outcomes.

In 2007, the Intergovernmental Panel on Climate Change (IPCC) [27] defined drought as being a prolonged absence of precipitations or a large deficit of precipitations, which leads to water scarcity for an activity or for a group or a period of time; an abnormally dry spell through the lack of precipitations and long enough to cause a serious hydrological imbalance. According to the United Nations Convention to Combat Desertification

TABLE 14.1 Drought Classification

Subrahmanyam [72]	Wilhite [89]	Tate and Gustard [77]	Maliva and Missimer [37]
Meteorological drought	Meteorological drought	Climatological drought (deficit in precipitations)	Meteorological drought
Climatological drought	Agricultural drought	Agro-meteorological drought (deficit of water in soil)	Climatological drought
Atmospheric drought	Hydrological drought	Hydrological drought (deficit regarding river flow)	Atmospheric drought
Agricultural drought	Socioeconomic drought	Hydrogeological drought (deficit of groundwater)	Agricultural drought
Hydrological drought		Operational drought (the conflict between demands and available resources)	Hydrological drought
Water management drought			Socioeconomic drought Water management drought

Sources: Maliva, R. and Missimer, T., *Arid Lands and Water Evaluation and Management*, Environmental Science and Engineering Series, Springer, 2012; Subrahmanyam, V.P., Incidence and spread of continental drought, WHO/IHD Report 2, International Hydrological Decade, Geneva, Switzerland, 1967; Tate, E.L. and Gustard, A., Drought definition: A hydrological perspective, in: Vogt, J.V. and Somma, F., eds., *Drought and Drought Mitigation in Europe*, Kluwer Academic Publishers, Dordrecht, the Netherlands, 2000, pp. 23–48; Wilhite, D.A. and Glantz, M.H., Understanding the drought phenomena: The role of definitions, in: Wilhite, D.A., Easterling Willam, E., and Deobarah, A., eds., *Planning of Drought: Towards a Reduction of Societal Vulnerability*, Westview Press, Boulder, CO, 1987, pp. 11–27.

[79], drought is defined as a natural phenomenon, which appears when precipitations record values below normal leading to hydrological imbalances that affect in a negative way the land's production systems.

The definition provided by the European Drought Observatory sustains that drought is caused by the lack of precipitations for a long period of time. Because the average values of precipitations present spatial variations, the definition of drought must be reported according to the characteristics of the studied area. Heim [23,24] defines drought as a recurrent phenomenon, which affects natural ecosystems as well as other economic and social sectors.

Pereira et al. [51] define drought as a temporary natural imbalance of available water resources due to a persistent period of below-normal precipitations volumes, with uncertain frequency, length, and severity; a phenomenon that cannot or can hardly be forecasted and that results in a diminishing of available water resources and of ecosystems' capacity of support.

Wilhite et al. [89] state that there are two ways to define drought: from a conceptual and an operational point of view. Conceptual definitions identify the limits of this phenomenon and are formulated in general terms. Operational definitions go to the depths of the problem with the following aims: to identify the beginning, the severity, and the duration of the drought in order to estimate its potential impact; to analyze the frequency; and to determine the probability of drought occurrence, and its intensity, duration, and spatial characteristics.

A summary of the main drought classifications is presented in Table 14.1 [37,72,77,89].

14.2 Regional Drought: State of Art and Knowledge Gaps

According to Rossi et al. [53], a comprehensive approach for studying regional drought problems includes the following:

1. Identification of meteorological causes and drought forecast
2. Evaluation of hydrological drought characteristics
3. Analysis of economic, environmental, and social effects of drought
4. Definition of appropriate measures for controlling drought effects

Even if a drought covers a large surface, it will be defined at regional level because droughts are regional in nature. From Section 14.1, it may be observed that many definitions of drought include references to the regional character of such an event. In 2004, Tallaksen and Van Lanen [75] defined drought as "a sustained and regionally extensive occurrence of below average natural water availability." Thus regional drought can be defined as the drought that refers to a region with a significant extension.

Panu and Sharma [49] proposed to study the regional behavior of droughts by analyzing the point behavior and then mapping the relevant parameters over a region or a country, an approach previously followed by other authors [25,74]. Another approach is to study regional variables like the area covered by the drought and the total deficit over that area [53,58,70,71,76,83]. Such investigations should proceed with a classification of at-site droughts into homogeneous regions in order to examine the drought properties and characteristics within each climatic region [35].

Regional features of drought have been analyzed by many authors. In 1976, Tase [76], followed shortly by Sen [70], proposed to analyze regional droughts with the help of a random field notion. This idea was extended by Santos [58], who succeeded in developing a statistical drought distribution model on the regional level—a model that was applied in Portugal [59].

In the last 35 years, researchers worldwide have developed several tools for regional analysis and classifications of droughts (or for drought regionalization):

- Factor analysis [57]
- Multiple regressions algorithm [31,41,50]
- Kriging [10]
- Pattern recognition [30]
- Neural networks [62]
- Cluster analysis [68]

There are some major challenges in debating about regional drought research. A first challenge is to develop suitable tools (methods, techniques) for forecasting the onset and termination points of regional droughts. Another challenging task is represented by the dissemination of regional drought research results for practical usage and wider application. Regional drought events primarily affect water availability but also have secondary impacts in terms of land degradation, ecosystem impacts, food provision and security, energy production, economic growth, and social stability. These secondary impacts and potential interrelations need to be carefully assessed at regional and local levels in order to enhance the efficiency of selected drought mitigation options.

14.3 Present Policy Framework for Regional Drought Management

Each region has a different exposure to drought. As it is difficult to define drought, it is even more difficult, or even impossible, to reduce the recurrence or frequency of such events. Thus, there is a high importance to develop a comprehensive understanding of the climatology of drought and to determine the features of these events at regional level.

A clear understanding of droughts and their behavior will improve the resilience of the affected regions and their capacity to recover after such events.

In drought management, it is not only the water issue that should be considered. The complexity of this phenomenon requires the involvement of experts from different fields such as agriculture, sustainable development, social department, environment protection, etc. In this way, it becomes more than necessary for a drought policy concept to be translated into an integrated management of drought, which is a more inclusive step, allowing better cooperation between the institutions involved in drought management.

Many of the world's countries have developed national policies for drought including community-based countries. The stakeholders' involvement from different levels of expertise, interest, and governance is a key problem in developing feasible integrated DMPs.

At regional level, nations must be prepared for situations when drought may simultaneously affect several (even all) crop-producing regions or watersheds. Therefore, regional DMPs are required to define specific actions to be taken by different administrative levels, to enhance preparedness and increase resilience to drought based on severity and for each water use sector affected. More importantly, an integrated DMP must include future measures and actions for post-drought events and especially post-evaluation of the processes and procedures implemented, in order to allow revision and updating to address possible deficiencies [93].

An integrated DMP, at regional level, should include, at least, the following issues:

- Regional drought triggers
- Regional drought indicators
- Regional drought characterization
- An assessment of the regional drought
- Medium- and long-term interventions to increase the regions' resilience
- Options to mitigate drought effects for each affected sector
- Involved regional stakeholders and their tasks
- Criteria to develop and improve regional plans
- Criteria for cooperation with other agencies/institutions from different decision levels
- Conceptual framework for assessing regional drought impact at socioeconomic level

The capacity of central, regional, and local authorities to react in the case of a drought event and to implement specific measures will highly influence the effectiveness of an integrated regional drought management. This stresses the critical need for clearly defining responsibilities at all decisional levels and for enhancing their capacity to understand and monitor drought events [93].

On what bases can a drought event be declared? Considering the previous chapters and paragraphs, stakeholders' involvement seems to be an important issue. It will once more be their role to define and establish a list of indicators and triggers necessary to set the conditions for declaring a drought event. This list must be easily understood not only by their authors but also by all interested persons or institutions, which may play a role in managing regional drought. Water availability, its use and restrictions should be the main elements in improving the solution to different factors affecting water availability. In addition, participatory tools and different conflict resolution techniques must be developed in order to assist the stakeholders in their process of analyzing the level of acceptability of the damages caused during a regional drought incident [93].

14.4 Regional Drought Monitoring and Forecasting

Drought monitoring and early warning are major components of drought risk management. A drought early warning system aims to detect the emergence or probability of occurrence and the likely severity of drought by analyzing data on climate and water supply trends. The results, with an accurate interpretation, can reduce impacts if delivered to decision-makers in a timely and appropriate format and if mitigation measures and preparedness plans are in place.

14.4.1 Methods and Tools for Regional Drought Monitoring

Drought is a phenomenon that develops very slowly and affects the entire water cycle, bearing direct impacts on vegetation cover. All these components need to be continuously monitored over long time periods. The short- to medium-term forecasting of the occurrence and likely evolution of droughts in different regions is important to support the development of efficient regional DMPs [83,84].

Improving drought monitoring is becoming increasingly important in addressing a wide range of societal issues, from food security and water scarcity to human health, ecosystem services, and energy production.

A major constraint to effective drought monitoring has always been the lack of a universally accepted definition of drought. Wilhite et al. [89] stated that the search for a single definition of drought is a hopeless exercise considering that drought definitions must be specific to each region, application, or impact.

According to Heim [23], first efforts in monitoring drought used some representation of precipitation. This approach was largely applicable to specific locations and not appropriate for regional comparisons.

Regional drought monitoring can be done in two ways:

1. By using meteorological observations and regional drought records [6]
2. With the help of remote-sensing technology [33]

Decision-makers need multiple indicators to understand the spatial pattern and temporal timescales within and between regions. Classical regional drought monitoring uses indicators such as the Palmer Drought Severity Index (PDSI) [47], Crop Moisture Index (CMI) [48], Surface Water Supply Index (SWSI) [61], and Standardized Precipitation Index (SPI) [38]. Despite the development of these indices, Wilhite [90] mentioned the existence of four other constraints in drought monitoring:

1. Temporal frequency of data collection
2. Spatial resolution
3. Use of a single indicator or index to represent the diversity and complexity of drought conditions and impacts
4. Lack of reliable drought-forecasting products

Moreover, Cai et al. [5] stated that these indicators may not be representative of regional conditions because meteorological observations are scarcely distributed and most of the underlying surfaces are not homogeneous.

According to Thiruvengadachari and Gopalkrishna [78], remote-sensing data are continuous datasets characterized by a constant availability, which can be used to detect the onset of drought, as well as its duration and magnitude.

There are three different ways of monitoring drought by using remote-sensing technology:

1. Detecting soil moisture and then establishing a relation between soil moisture and drought
2. Monitoring and determining vegetation index
3. Analyzing land surface temperature, which is a relevant indicator of the energy balance in processes at the earth's surface on regional and global scales [85]

14.4.2 Methods and Tools for Regional Drought Forecasting

An effective integrated regional DMP includes a compulsory section: regional drought forecasting. This section must integrate elements of climate, water supply and water use monitoring, early warning systems, etc. All persons involved in preparing and managing the elements of this section must have a good knowledge in these fields and must be well trained in using and disseminating the relevant information [93].

Decision-makers must have accurate drought-monitoring information to respond successfully during drought events. To forecast drought, it is important to know the causes of drought.

Drought forecasting is generally based on drought indicators computed using dynamic or statistical model simulations of drought-related variables [36,43]. A significant percent of drought prediction studies are based on the SPI [38] with the input precipitation derived from dynamic weather/climate models, which provide valuable information [15,16,44,94].

According to some authors, precipitation forecasts are subject to high uncertainty because existing models exhibit very low skills in predicting precipitation with a few months' lead time [1,21,32,34,42].

14.5 Regional Drought: Prevention, Identification, Assessment, and Mitigation

Drought is a natural hazard, which has a slow onset and evolves over months or even years. It may affect a large region and cause little structural damage. The impacts of drought can be reduced through preparedness and mitigation, which include the following components: prediction, monitoring, impact assessment, and response.

Many countries have generated drought management policies and improved on existing ones in order to mitigate the impacts of drought and to prevent severe water shortages and dramatic consequences on the economy, the society, and the environment.

DMPs should be prepared in advance, based on relevant country-specific legislation and careful studies concerning the characterization of the drought in the region, its effect, and mitigation measures [19].

According to Smakhtin and Hughes [65], drought operational definitions, which are based on scientific reasoning and follow the analysis of certain amounts of hydrometeorological data, are beneficial in developing mitigation strategies and preparedness plans. The major output, building upon national initiatives, will be a coordinated regional framework for drought monitoring, early warning, prediction, and management, accompanied by a set of guidelines and tools for the development of regional, national, and local drought policies and plans.

According to Bazza [2], drought preparedness refers to pre-drought activities designed to improve institutional and operational capabilities for responding to a drought event. It corresponds to the planning of activities in advance of a drought event. Drought preparedness should include a characterization of the regional drought event, an assessment of risks and impacts, tools for regional drought prediction, and a regional DMP.

Drought characterization involves the collection of regional information for selecting and developing specific regional drought indicators for drought monitoring and for defining the triggers, which indicate the beginning and the end of a drought incident, as well as indicator thresholds so as to activate mitigation measures [69].

Prediction and early warning are essential components of regional drought preparedness plans. Their aim is to improve the efficiency of regional drought planning by providing reliable information to support regional drought risk assessment and the selection and implementation of mitigation actions.

According to the Xerochore project research team,

> a drought mitigation strategy is based on options that are technically feasible, economically viable, socially acceptable and environmentally sustainable at the spatial scale of application. In this regard the considerable effort for assessing water management options and strategies in terms of effectiveness and efficiency should be enhanced by explicitly considering the issues of uncertainty and risk, in order to facilitate more informed planning and decision-making processes. Furthermore, the evaluation of [an] alternative for drought mitigation options requires a multi-disciplinary approach for adapting proposals to local conditions and specificities, explicitly addressing financial constraints, cultural and social aspects and regional development priorities [93].

Rossi [55] mentioned that an effective identification and forecasting system for regional drought that is able to promptly warn of the onset of this phenomenon and to follow its evolution in space and time represents the prerequisite for a successful mitigation strategy.

Regional drought identification is mainly done by using drought indices. Among the several proposed drought-monitoring indices, the SPI and the Reconnaissance Drought Index (RDI) have found widespread application for describing and comparing droughts from different time periods and regions with different climatic conditions.

However, according to Cancelliere et al. [8], limited efforts have been made to analyze the role of the SPI for drought forecasting. Cancelliere et al. proposed a stochastic model to forecast SPI values at short to medium term, as well as to estimate transition probabilities of SPI classes corresponding to drought of different severities [7]. Despite such efforts, forecasting when a drought is likely to begin or to come to an end is still a difficult task [11].

From social and economical points of view, drought is one of the major water-related climatic events that can easily lead to a disaster. Due to its possible extent in time and space, drought may have serious environmental, social, and economic impacts. These impacts depend not only on the duration, severity, and spatial extent of the precipitation deficit, but also on the environmental and socioeconomic vulnerability of affected regions [17,18,80,81].

The socioeconomic impacts of regional droughts depend on the physical, social, environmental, and economic characteristics of the affected region. Due to continuous population growth, there is an increasing pressure on soil resources. Moreover, increasing land degradation, together with changes in land use and land cover, water demand and use, as well as projected climate change scenarios, leads to more research on drought, where planning is crucial to averting and mitigating drought disasters.

Because past efforts in drought forecasting and monitoring have focused mainly on climatic aspects of drought, currently there is an insufficiency of drought preparedness and mitigation methods that adequately address the socioeconomic effects of regional droughts [81].

14.6 Regional Drought Indices

14.6.1 Indicators Based on Climatic Data

14.6.1.1 Palmer Drought Severity Index

One of the most used indicators in drought monitoring is the PDSI, which uses temperatures and precipitations from a specific location to estimate soil humidity using a simplified model of water balance. This indicator is based on determining the water balance in soil using precipitations and water reserves from soil as inputs and evapotranspiration as the output [47] (see Table 14.2).

The PDSI is a standardized index that can be used for comparative determinations between different regions and periods of time.

TABLE 14.2 Climate Characterization as Function of PDSI Values

PDSI Values	Climate Characterization
PDSI > 4	Extremely wet
3 < PDSI < 3.99	Very wet
2 < PDSI < 2.99	Moderately wet
1 < PDSI < 1.99	Lightly wet
0.5 < PDSI < 0.99	Incipient humid period
0.49 < PDSI < −0.49	Almost normal
−0.5 < PDSI < −0.99	Incipient dry period
−1 < PDSI < −1.99	Lightly dry
−2 < PDSI < −2.99	Moderately dry
−3 < PDSI < −3.99	Severely dry
PDSI < −4	Extremely dry

Source: Palmer, W.C., Meteorological drought, U.S. Weather Bureau Research Paper 45, 1965, 58pp.

The PDSI can be calculated using the following relation:

$$PDSI_i = 0.897 \cdot PDSI_{i-1} + \frac{Z_i}{3} \tag{14.1}$$

where

$PDSI_i$ and $PDSI_{i-1}$ represent the drought index for the current period and the previous period, respectively

Z_i represents the anomaly indicator of water reserves from soil during the current period reported to its normal value

$$Z = K \cdot d \tag{14.2}$$

where

K is a weight climatic factor in order to be able to compare the PDSI values at temporal and regional level

d represents the deviation of water reserves from soil for the considered interval against the normal value for the same period:

$$d = P - \hat{P} \tag{14.3}$$

where

P represents the total precipitations for the considered period

$\hat{P}$ represents the value of precipitations corresponding to the climatic point of view to the existent conditions

$\hat{P}$ is calculated from the equation of soil water balance:

$$\hat{P} = \overline{ET} + \overline{R} + \overline{RO} - \overline{L} \tag{14.4}$$

where

$\overline{ET}$ represents the evapotranspiration

$\overline{R}$ is the restoring soil water reserve

$\overline{RO}$ is the loss due to seepage and runoff

$\overline{L}$ is the reduction of soil water reserve when rainfall is below potential evapotranspiration in the period considered

The terms of the equation are multiannual average values for the considered period [47].

14.6.1.2 Crop Moisture Index

It was proposed by Palmer in 1965 to monitor plant growth conditions. The CMI highlights the contribution of relatively low rainfall during a drought which over short intervals leads to increasing soil moisture and thus easy access to water for plants. This index is calculated weekly and is used to monitor agricultural drought and water reserves over short periods of time. It can be used for making decisions on the application of watering in order to eliminate water stress [47].

The CMI is a noncumulative index based on the difference between current actual evapotranspiration and the estimated one (climatological value) for the same period. It is calculated using the following equation proposed by Palmer [48]:

$$CMI = ET_{aobserved} - ET_{aexpected} \tag{14.5}$$

TABLE 14.3 CMI Drought Severity Classes for Wet and Dry Periods

CMI Values	Class
≥3	Excessively wet, some fields flooded
2–2.99	Too wet, standing water in some fields
1–1.99	Prospects good, but fields too wet
0–0.99	Moisture adequate for immediate needs
−0.99 to 0	Conditions improved but need more rain
−1 to 1.99	Prospects improved but still only fair
−2 to −2.99	Drought cased, but more rain needed
≤−3	Situation still serious, rain badly needed

Source: Palmer, W.C., *Weatherwise*, 21, 156, 1968.

Negative values indicate a deficiency in evapotranspiration, which could lead to drought conditions, while positive values show that actual evapotranspiration was higher than the estimated value [63] (see Table 14.3).

14.6.1.3 Surface Water Supply Index

This indicator was proposed to complete Palmer's indicator with humidity conditions from several American states and regions where snow represents a major component of hydrological balance. The SWSI is an indicator of surface hydrology. Here, climatic and hydrologic elements are incorporated in a single indicator that is valid for a hydrographic basin. The advantage of the SWSI is that its values can be standardized for comparisons between different hydrological basins [61].

The SWSI is determined with the following relation:

$$SWSI = \frac{\left[\left(a \cdot PN_{ZP}\right) + \left(b \cdot PN_{P}\right) + \left(c \cdot PN_{S}\right) + \left(d \cdot PN_{AC}\right) - 50\right]}{12} \tag{14.6}$$

The terms from the previous relation have the following meanings:

PN represents the probability of not exceeding (%)
ZP is the snow accumulated on soil
P represents the precipitations
S is the leakage at the outlet of the catchment area
AC is the change in the volume of water in the reservoirs from the analyzed catchment
a, b, c, d are the weights of each element noting that $a + b + c + d = 1$

The SWSI requires monthly data for liquid precipitation, solid precipitation, river flows, and leakages in characteristic sections (basin's outlet) depending on the water volume changes in reservoirs. Using these data, a statistical analysis is performed to obtain a curve of insurance. Based on these curves, corresponding probabilities of not exceeding are determined and the SWSI is calculated. The sum of all these components is centered on 0 by reducing with 50% and is divided by 12 in order to determine the limits of the index domain between −4.2 and 4.2 [61].

The SWSI is an index that does not present major difficulties in calculation and provides a characterization of water resources in the catchment. Its limitations appear in large river basins with a pronounced variety of hydrological conditions. Discontinuous measurements at some stations may also present difficulties. Putting into operation new hydraulic structures will change the weights of balance components [61].

14.6.1.4 Reclamation Drought Index

The RDI is calculated at basin level and incorporates temperature, precipitation, snow, flow rate, and reservoir levels as inputs (see Table 14.4). By including temperature, evaporation is taken into account. As the index is unique for each river basin, comparisons are limited between different basins [88].

TABLE 14.4 Climate Classification Using RDI Values

RDI	Classification
4.0 and above	Very humid
Between 1.5 and 4.0	Moderately humid
Between 1 and 1.5	Normal to a light humidity
Between 0 and −1.5	Normal to a light drought
Between −1.5 and −4.0	Moderate drought
−4.0 or less	Extreme drought

Source: Weghorst, K., *The Reclamation Drought Index: Guidelines and Practical Applications*, Bureau of Reclamation, Denver, CO, 1996, 6pp.

14.6.1.5 Regional Streamflow Deficiency Index

Stahl [68] developed this indicator to characterize hydrological drought. The Regional Streamflow Deficiency Index (RSDI) is based on daily data flow and does not consider seasonal influence on drought. This index does not indicate the extent of the drought (only quantifies the duration of a binary time series) and drought severity is quantified in terms of area affected, making it impossible to compare the hydrological drought between different stations.

To represent the cumulative deficit of the flow, an index based on a cluster (regional) is calculated [67]. Daily deficit of the indicators $DI(t)$ from all G stations belonging to a C cluster is resumed and normalized by n (representing the number of stations from that cluster):

$$RDI_c(t) = Z\frac{1}{n}\sum_{GZ1}^{n} DI_G(t) \tag{14.7}$$

Therefore, the RSDI represents the daily fraction of watersheds from a cluster affected by flow deficit. Given the spatial severity of the flow deficit, a time series of this indicator can then be used for regional analyses.

14.6.1.6 Cumulative Water Balance Index

Denisson et al. [13] proposed a cumulative water balance index to measure regional drought stress. The index is a sum over the period T of the difference between precipitation and reference evapotranspiration:

$$ICBA_t = \sum (P_t - ET_{0t}) \tag{14.8}$$

where

t represents the considered period of time
P_t represents the precipitations over that period
ET_{0t} is the reference evapotranspiration

A modified Penman equation is used to calculate evapotranspiration using solar radiation, air temperature, vapor pressure, and wind speed. The index has been tested in California and provides an additional methodology for monitoring risk of fire occurrence.

14.6.1.7 Standardized Precipitation Index

The SPI was designed to quantify the precipitation deficit for multiple timescales. These timescales reflect the impact of drought on the availability of the different water resources. Soil moisture conditions respond to precipitation anomalies on a relatively short scale. Groundwater, streamflow, and reservoir storage

TABLE 14.5 Climate Classification Based on SPI Values

SPI	Classification
≥2	Extremely wet
1.5–1.9	Very wet
1–1.49	Moderately wet
0–0.99	Near normal
0 to −0.99	Near normal
−1 to −1.49	Moderately dry
−1.5 to −1.99	Severely dry
≤−2	Extremely dry

Source: Guttman, N.B., *J. Am. Water Resour. Assoc.*, 35(2), 311, 1999.

reflect the longer-term precipitation anomalies. For these reasons, McKee et al. [38] originally calculated the SPI for 3-, 6-, 12-, 24-, and 48-month timescales [92].

The SPI is a probability index that considers only precipitation. It is based on the probability of recording a given amount of precipitation, and the probabilities are standardized so that an index of zero indicates the median precipitation amount (half of the historical precipitation amounts are below the median and half are above the median). The index is negative for drought and positive for wet conditions. As the dry or wet conditions become more severe, the index becomes more negative or positive.

McKee et al. [38] used the classification system shown by the SPI values in Table 14.5 to define drought intensities resulting from the SPI. They also defined the criteria for a drought event for any of the timescales. A drought event occurs at any time that the SPI is continuously negative and reaches an intensity of −1.0 or less. The event ends when the SPI becomes positive. Each drought event, therefore, has a duration defined by its beginning and end, and a specific intensity for each month that the event continues. The positive sum of the SPI for all the months within a drought event can be termed the drought's "magnitude" [92].

14.6.1.8 Rainfall Anomaly Index

Van Rooy [82] developed the rainfall anomaly index. This index is calculated on weekly, monthly, and yearly timescales. The timescale is chosen based on rainfall distribution. In areas with long dry periods a larger timescale is used. Average weekly, monthly, and annual rainfalls are used for the calculation of relative drought. Classification results are based on the 10 drought events recorded. Oladipo [45] compared this index with the PDSI and did not find major differences in the results.

$$RAI = \pm 3\left(\frac{P-\bar{P}}{\bar{E}-\bar{P}}\right) \tag{14.9}$$

where

P is the precipitation measured
$\bar{P}$ is the average rainfall
$\bar{E}$ represents average extreme values

For positive anomalies, $\bar{E}$ is the average of the 10 heaviest rainfalls recorded, while the values of milder events are used for negative anomalies.

14.6.1.9 Palfai Drought Index

The core value of this index is calculated (see Table 14.6) for the period from April to August using the following formula [46]:

$$PAI_0 = \frac{t_{IV-VIII}}{P_{X-VIII}} \cdot 100 \ (°\text{C}/100 \text{ mm}) \tag{14.10}$$

TABLE 14.6 Characterization of Drought in Relation to the Palfai Index Is Made according to the Following Values

P.A.I. Values	Drought Characterization
6 < PAI < 8	Moderate drought
8 < PAI < 10	Average drought
10 < PAI < 12	Severe drought
PAI ≥ 12	Extreme drought

Source: Palfai, I. et al., Some methodological questions of the European drought sensitivity map, in: *Proceedings of the International Workshop on Drought in the Carpathians Region*, Budapest-Alsogod, Hungary, May 3–5, 1995, pp. 131–142.

where

$t_{IV-VIII}$ represents the average monthly mean air temperatures from April to August (°C)

P_{X-VIII} is the sum of monthly precipitation from October to August (mm)

The index is adjusted using three factors: K_t for excessive temperatures ($t > 30$°C), K_p for precipitations, and K_{gw} for groundwater.

$$K_t = \sqrt[6]{\frac{n+1}{\bar{n}+1}}. \tag{14.11}$$

where

n is the number of days with extreme heat ($t > 30$°C) during June–August

$\tilde{n}$ is the multiannual average of n

$$K_p = \sqrt[4]{\frac{\tau_{\max}}{\overline{\tau}_{\max}}} \tag{14.12}$$

where

$\tau_{\max}$ is the length of the longest period without precipitation (or precipitation summed up from successive days under 5–6 mm) between June 15 and August 15

$\overline{\tau}_{\max}$ is the multiannual average of $\tau_{\max}$

$$K_{gw} = \sqrt{\frac{H}{\overline{H}}} \tag{14.13}$$

where

H represents the average depth of groundwater between November and August

$\overline{H}$ is the multiannual average of H

This factor is used in particular for river meadows. The final adjusted value of the Palfai index is [46]

$$PAI = K_t \cdot K_p \cdot K_{gw} \cdot PAI_0 \tag{14.14}$$

14.6.1.10 Pinna Index

The Pinna combination index is used to classify tropical and subtropical climates in the regions of south-eastern Europe and takes into account the average annual temperature and annual precipitation, respectively, from the rainfall and temperature corresponding to the driest months [95].

$$I_P = \frac{1}{2}\left(\frac{P}{T+10} + \frac{12P_d'}{T_d'+10}\right) \tag{14.15}$$

where P and T are the annual precipitations and average annual temperatures while P_d' and T_d' are the precipitations and temperatures of the driest month. The interpretation is as follows:

$$I_p < 10 \quad \text{dry climate}$$

$$10 < I_p < 20 \quad \text{half-Mediterranean climate}$$

For values greater than 20, Pinna does not provide any classification (indications). It can be seen from the earlier equation that the Pinna index is based on DeMartonne's indicator formula and is a combination of annual and monthly DeMartonne indicators. It may be noted that the final ratio is the DeMartonne formula for the driest month of the year without Pinna defining a dry month.

According to Gaussen [20], a month is defined as being dry when $P < 2T$, where P and T are the monthly values of rainfall and temperature. Given the importance of air humidity in analyzing biological drought, Gaussen [20] offers several additional features to define a droughty month. He characterizes a month as being dry when the following conditions are met:

1. $P < 10$ mm and average monthly temperature is lower than 10°C.
2. $P < 25$ mm and average monthly temperature is between 10°C and 20°C.
3. $P < 50$ mm and average monthly temperature is between 20°C and 30°C.
4. $P < 75$ mm and average monthly temperature is higher than 30°C.

14.6.1.11 Effective Drought Index

Byun and Wilhite [4] have developed the effective drought index (EDI), which is an intensive measure that considers daily water accumulation, with a weighting function over time (see Table 14.7). The following equations are used to calculate EDI:

$$EP_i = \sum_{n=1}^{i}\left[\frac{\sum_{m=1}^{n} P_m}{n}\right] \tag{14.16}$$

$$DEP = EP - MEP$$

TABLE 14.7 EDI Characterization

EDI	Characterization
EDI < −2	Extreme drought
−2 ≤ EDI ≤ −1.5	Severe drought
−1.5 ≤ EDI ≤−1.0	Moderate drought
−1.0 ≤ EDI ≤ 1	Normal conditions

Source: Byun, H.R. and Wilhite, D.A., *J. Climate*, 12, 2747, 1999.

where

MEP is the average effective rainfall for each day of the year

DEP represents EP daily value deviations from the mean

The daily standard deviation value is determined by the following relation:

$$EDI = \frac{DEP}{SD(DEP)} \tag{14.17}$$

EP_i represents the valid precipitation accumulations and P_m is the level of precipitations for 1 day, "m" days before the specific day; "i" starts from 365. Thus, EP becomes the valid accumulation of precipitations for 365 days from a precise date. DEP represents EP deviation from MEP (EP average for 30 years). When DEP is negative for two consecutive years, "i" becomes 366 and the calculations are repeated. Therefore, the drying effect of the soil because of a severe drought that occurred a few years ago is reflected in EDI. EDI is the element that enables comparisons of drought severity between two or more areas without being influenced by the climatic differences between them.

For drought operational analysis, precipitation in normal conditions (PRN) will be calculated. PRN daily values are determined according to the period for which DEP values were determined using the following relationship:

$$PRN_j = \frac{DEP_j}{\sum_{N=1}^{j}(1/N)} \quad \text{where } j \text{ is the current period.} \tag{14.18}$$

The result is the EDI standardized index:

$$EDI_J = \frac{PRN_J}{ST(PRN_J)} \tag{14.19}$$

where ST(PRN) represents the standard daily values of PRN.

14.6.2 Remote-Sensing Drought Indicators

Scientists use data collected by remote sensing—typically via satellites, radar, or aerial photography—as an additional source of drought indicators. The satellite-sensor data are consistently available and can be used to detect the onset of drought, its duration, and its magnitude [78]. Vegetative conditions over the world are reported occasionally by the National Oceanic and Atmospheric Administration's (NOAA) National Environmental Satellite Data and Information System (NESDIS) using the advanced very high-resolution radiometer (AVHRR) data [29].

Drought indicators can be derived for any world region using these data. The characteristic spatial resolution of 10 km (at this resolution, well-calibrated long-term historical data are freely available) is likely to be coarse for effective drought monitoring at small scales.

The moderate-resolution imaging spectrometer (MODIS) is an advanced narrow-bandwidth sensor, from which composite reflectance data are made available at no cost by the National Aeronautics and Space Administration (NASA) and the U.S. Geological Survey (USGS), through the Earth Resources Observation Systems (EROS) data center [28].

14.6.2.1 Normalized Difference Vegetation Index

The Normalized Difference Vegetation Index (NDVI) is calculated from the visible and near-infrared light reflected by vegetation. Healthy vegetation absorbs most of the visible light that hits it and reflects a large portion of the near-infrared light. Unhealthy or sparse vegetation reflects more visible light and less near-infrared light [26,56].

Nearly all satellite vegetation indices employ this difference formula to quantify the density of plant growth on the earth: near-infrared radiation minus visible radiation divided by near-infrared radiation plus visible radiation. The result of this formula is called the NDVI. Written mathematically, the formula is

$$NDVI = \frac{NIR - VIS}{NIR + VIS} \tag{14.20}$$

Calculations of *NDVI* for a given pixel always result in a number that ranges from minus one (−1) to plus one (+1); however, no green leaves gives a value close to zero. A zero means no vegetation and close to +1 (0.8–0.9) indicates the highest possible density of green leaves [26,56].

14.6.2.2 Vegetation Condition Index

Satellite NDVI data have been used in classifying the vegetation condition. Kogan [29] suggested an approach to monitoring vegetation condition based on minimum and maximum NDVI values compiled per pixel over time. Kogan [29] states that available moisture and natural resources determine the NDVI minimum while other values, including the historical maximum, are determined by the weather. Kogan [29] used this NDVI statistical range to develop the Vegetation Condition Index (VCI), an indicator of environmental stress.

The VCI is NDVI normalized for each pixel on the basis of the maximum statistical range over the historical record of available imagery [52].

This indicator refers to the vigor of vegetation cover and is established with the following relationship:

$$VCI = \frac{NDVI - NDVI_{\min}}{NDVI_{\max} - NDVI_{\min}} \tag{14.21}$$

where $NDVI_{max}$ and $NDVI_{min}$ represent maximum and minimum values of NDVI calculation period based on a string of 20 years. The VCI refers to NDVI variation as it is a superior indicator to the NDVI. However, VCI accuracy depends on NDVI measurements and on the quality of NDVI data (in particular, the extreme values). VCI values are positive and greater than 0. Values very close to 0 indicate a plant in the worst state (pronounced hydric stress), while values tending to 1 show a situation corresponding to a good water supply from the soil.

14.6.2.3 Vegetation Drought Response Index

The Vegetation Drought Response Index (VegDRI) is a new drought-monitoring tool that integrates satellite-based NDVI observations, climate-based drought index data, and several biophysical characteristics of the environment to produce an indicator that expresses the level of drought stress on vegetation. The VegDRI integrates concepts from both the remote-sensing-based NDVI and the climate-based drought index approaches to produce 1 km resolution maps that characterize the intensity and spatial pattern of drought-induced vegetation stress over large areas. In the VegDRI approach, the 1 km NDVI images provide detailed spatial patterns of vegetation conditions, which are analyzed in combination with dryness information represented in the climate-based drought index data to identify and characterize the intensity and spatial extent of drought conditions. Biophysical parameters such as the land cover type, water-holding capacity of soil, irrigation status, and ecological setting of an area are also analyzed because these environmental characteristics can influence specific climate–vegetation interactions. The VegDRI was developed in a collaborative research effort between the National Drought Mitigation Center (NDMC) and USGS's

Earth Resources Observation and Science (EROS) Center and is designed to be a near-real-time, national drought-monitoring tool for the conterminous United States. The 1 km VegDRI maps depict more spatially detailed, drought-specific information related to vegetation than traditional drought-monitoring tools. In addition, this information is provided on relevant spatial and temporal scales to decision-makers working at local to national levels [86].

14.7 Dealing with Regional Drought under Water–Land–Energy Systems Management

The foundation on which human societies rely for their existence, for productive development, and for their security and well-being consists of energy, land, and water resources and their associated ecosystems. These resource sectors are coupled to one another by supply–demand relationships that support human socioeconomic activities and the ecosystems on which societies rely for critical services [12,40,66].

Extreme climate events such as regional droughts and associated heat waves have significant impacts on the energy–water–land interfaces. These impacts can be seen as changes in cropping and grazing and accompanying wildfire damage. Moreover, these changes can reinforce and intensify individual impacts on land and water resources. To a lesser extent, these changes affect water and land use, which will in turn impact on energy demand and production [64].

Potential climate impacts (including regional droughts) on the supply–demand interface linkages can include the following:

1. Changes in the quantity and timing of hydrographic cycle flows will result in changes in reservoir storage capacity and in hydropower generation. These changes will also impact downstream uses such as water availability for biomass irrigation, thermoelectric power plant cooling, as well as other urban center uses.
2. Regional drought can also mean shifts in heating and cooling degree-days, which will alter timing for peak power demands and affect loads on the grid and transmission systems. Periods of prolonged regional drought combined with high daily temperatures can impact biomass production by degrading growth and yields and/or requiring irrigation, which increases water demand.
3. Competing water demands in arid or over-allocated water systems under climate stress (regional drought and/or regional heat wave) will mean less water availability for thermoelectric power generation, urban center supplies, irrigation of biomass, etc.
4. Regional droughts and elevated temperatures that reduce surface water supplies and watershed flow timing can also affect hydropower and thermopower generation as well as the production and processing of biomass for bioenergy [64].

14.8 Regional Drought: Policy Decision-Making under Risks, Vulnerabilities, and Uncertainties

Risk-based drought management is multifaceted and requires the involvement of a variety of stakeholders. From a drought management policy perspective, capacities in diverse ministries and national institutions are needed. Often it is necessary to go beyond past attempts to manage drought risk based on a reactive crisis–response approach, by promoting drought mitigation and preparedness at the national and regional levels. For this purpose, the development of drought information tools is fundamental for the implementation of DMPs and to support real-time decision-making.

The elements for a drought risk reduction framework can be summarized into four main areas of endeavor, all of which consider priorities set by the UN International Strategy for Disaster

Reduction (ISDR), the Hyogo Framework for Action, regional strategies, and thematic risk reduction documents [80]:

- Policy and governance as an essential element for drought risk management and political commitment
- Drought risk identification, impact assessment, and early warning, which include hazard monitoring and analysis, vulnerability and capability analysis, assessments of possible impacts, and the development of early warning and communication systems
- Drought awareness and knowledge management to create the basis for a culture of drought risk reduction and resilient communities
- Effective drought mitigation and preparedness measures to move from policies to practices in order to reduce the potential negative effects of drought

All of these elements need strong political commitment, community participation, and consideration of local realities and indigenous knowledge. The international and regional communities also play an important role in coordinating activities, transferring knowledge, supporting project implementation, and facilitating effective and affordable practices.

According to the UN/ISDR [80], a regional drought policy and plan should specify the respective roles of different regional stakeholders and available resources that will be required to implement appropriate drought risk reduction activities. Although regional drought policies will vary to reflect local needs, drought risk reduction and preparedness policies should also address the following concepts:

- Provide for effective participation of nongovernmental organizations (NGOs) and the population at the local and regional levels in policy planning, decision-making, and implementing and reviewing regional action programs
- Be thorough in vulnerability, risk, capacity, and needs assessments, highlighting the root causes of the issues related to drought at national, subnational, local, and trans-boundary scales
- Focus on strengthening the capacities of governments and communities to identify, assess, and monitor drought risks at regional levels for effective development planning, including strengthening of people-centered early warning systems and preparedness
- Incorporate both short- and long-term strategies to build the resilience of governments and communities to reduce the risks associated with drought, emphasize implementation of these strategies, and ensure they are integrated with national and regional policies for sustainable development
- Link early warning indicators of drought with appropriate drought mitigation and response actions to ensure effective regional drought management
- Allow for modifications to be made in response to changing circumstances and be sufficiently flexible at the local level to cope with different socioeconomic, biological, and geophysical conditions
- Promote policies and strengthen institutional frameworks, which develop cooperation and coordination, in a spirit of partnership, between the donor community, governments at all levels, local populations, and community groups, and facilitate access by local populations to appropriate information and technology
- Designate agencies and stakeholders responsible for carrying out drought mitigation and response actions, and demand regular review of, and progress reports on, their implementation
- Strengthen drought preparedness and management, including drought contingency plans at the local, national, subregional, and regional levels, which take into consideration seasonal to interannual climate predictions.

14.9 Summary and Conclusions

Exposure to drought varies regionally and over time, and there is little, if anything, that can be done to alter its occurrence, because drought is a normal occurrence of climate. Development of regional networks for drought preparedness would enhance regional capacity to share lessons learned in drought monitoring, prediction, preparedness, and policy development. Many regions have already developed and improved their DMPs but currently there is an insufficiency of drought preparedness and mitigation methods that adequately address the socioeconomic effects of regional droughts. Effective information and early warning systems are the foundation for effective regional drought policies and plans, as well as effective network and coordination between central, regional, and local levels. Classical regional drought monitoring uses climatological indicators (e.g., PDSI, CMI, SWSI, SPI, Palfai), but these indicators may not be representative of regional conditions and remote-sensing indicators may be preferred.

Even though there is a "flood" of information regarding different aspects of regional drought management, there persists a scarcity of a coherent and integrated package of reliable scientific and practical information for interested stakeholders, mostly from the socioeconomic field, as regional drought management continues to be a "hot" problem in many regions.

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15

Rainfall Management for Sustainable Agriculture

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Abstract Agriculture is the means of ensuring household and national food security and a driving force for economic transformation. Sustainable agriculture is aimed at improving the productivity of smallholder agriculture through adopting soil and water conservation techniques. This contributes to food security in the country. Sustainable agriculture is increasingly gaining recognition in southern Africa as involving a group of technology interventions that have the potential to increase yields from a wide range of crops, through the conservation of soil, water, nutrients, and farm power.

Water and soil nutrient management form a critical component of agricultural production. The most important constraints to rain-fed crop production are drought and poor soil fertility. Secondary factors that worsen the food security plight among poor and vulnerable members of the smallholder farming community that are usually assisted by relief organizations include late planting as a result of lack of draft power for timely tillage and poor access to inputs like manure and fertilizer to ameliorate the effects of exhausted soils with low organic matter content on crop growth and yield. To improve crop production in marginal rainfall regions, cultural practices that conserve and extend the period of water availability to the crop are essential, if the full benefits of soil fertility improvements through organic and inorganic fertilizers are to be realized.

Thus, sustainable agriculture is needed to develop farming systems that are productive and profitable, conserve the natural resource base, protect the environment, and enhance health and safety, and to do so over the long term. It aims at achieving creative and innovative conservation and production practices that provide farmers with socially acceptable, economically viable, and

environmentally sound alternatives or options in their farming systems. Climate and soil are the two most critical factors that determine the ultimate sustainability of agricultural systems. As temperature increases and precipitation decreases, the development of sustainable farming systems becomes difficult. The potential for erosion by water and wind also tends to increase with increasing temperatures. Both these degradation processes progressively accelerate with increasing aridity because of the associated decline in soil organic matter and less natural vegetation to control erosion. This chapter focuses on strategies to improve rainfall management in sustainable agriculture practices.

15.1 Introduction

Food and fiber productivity has soared dramatically due to new technologies, mechanization, increased chemical use, specialization, and government policies that favor maximizing production. These changes have enabled farmers with reduced labor demands to produce the majority of the food and fiber. Although these changes have many positive effects and reduced risks in farming, there have also been significant costs. Prominent among these are topsoil depletion, groundwater contamination, the decline of family farms, continued neglect of the living and working conditions for farm laborers, increasing costs of production, and the disintegration of economic and social conditions in rural communities [8].

Environmental degradation is a challenge resulting from bare slopes and rivers eroding the soil. Soil erosion by water is the major form of environmental degradation and is severe in unvegetated highlands [16]. In addition to the physical loss of soils, mining of soil nutrients through continuous cultivation induced by the population pressure is the other factor contributing to the declining agricultural productivity [23]. The traditional practices of soil fertility replenishment, such as fallowing, and the use of cattle dung and crop residues have now largely been abandoned. This is because of the land shortage, as well as the use of dung and crop residues for domestic energy production purposes as the forests and trees have become scarce. Degradation of environmental resources deprives the rural population of basic livelihood assets and contributes to their food insecurity and poverty.

Severe droughts and the accompanying crop failures and food shortages are recurring problems that affect agricultural production [6]. The challenges to agriculture in semiarid regions are lack of labor or farm power, low yields, and environmental degradation. The farmers, unlike those in many other parts of the world, do not have machines and equipment to help them. The AIDS pandemic and malaria make this labor shortage even more acute. Sustainable agriculture eliminates ploughing and controls weeds better than conventional farming, so it needs less labor. Thus, sustainable agriculture can significantly raise yields and can provide many different types of food and feed. It protects the land and feeds the soil. It can halt and even reverse land degradation. That means cleaner rivers and less sediment to clog reservoirs and irrigation channels.

Water is a vital component of agricultural production. It is essential to maximize both yield and quality. Water has to be applied in the right amounts at the right time in order to achieve the right crop [7]. At the same time, the application of water should avoid waste of a valuable resource and be in harmony with the environment as a whole [4]. Understanding, measuring, and assessing how water flows around the farm, and recognizing how farming practices affect flows, will help farmers to manage water efficiently and reduce pollution risks.

Careful and effective water management helps farmers to continue to produce profitably. Farmers aim to guarantee that the safety and quality of the water they use will satisfy the highest expectations of the food industry and consumers. In addition, on-farm practices should ensure that water management is carried out under sustainable economic, social, and environmental conditions [21].

Sustainable agriculture is vital in maintaining or increasing crop productivity through conservation of soil, water, nutrients, and/or draft power and is gaining recognition in the region. This chapter is an effort to highlight water conservation practices of sustainable agriculture [12].

15.2 Sustainable Agriculture

Sustainable farming strategies are employed to increase food production levels even under drought conditions. Sustainable agriculture is a loosely defined term that encompasses a range of strategies for addressing many of the problems that afflict agriculture worldwide [15]. The ultimate goal or the ends of sustainable agriculture is to develop farming systems that are productive and profitable, conserve the natural resource base, protect the environment, and enhance health and safety, and to do so over the long term. The means of achieving this is low-input methods and skilled management, which seek to optimize the management and use of internal production inputs (i.e., on-farm resources) in ways that provide acceptable levels of sustainable crop yields and livestock production and result in economically profitable returns. This approach emphasizes such culture and management practices as crop rotations, recycling of animal manures, and conservation tillage to control soil erosion and nutrient losses and to maintain or enhance soil productivity. Low-input farming systems minimize the use of external production inputs (i.e., off-farm resources), such as artificial fertilizers and pesticides, wherever and whenever feasible and practicable: to lower production costs; to avoid pollution of surface and groundwater; to reduce pesticide residues in food; to reduce a farmer's overall risk; and to increase both short- and long-term farm profitability. Another reason for the focus on low-input farming systems is that most high-input systems fail because they are not either economically or environmentally sustainable over the long term [18–20].

Arid and semiarid environments are the most seriously degraded in terms of soil erosion and associated nutrient runoff losses and organic matter depletion. Soil moisture deficiencies eventually led to reduced soil fertility. The combined effect of water deficiency on shallow as well as deep-root plants was progressive decline in the plant conditions. Leaf and stem loss in herbaceous and woody plants was followed by plant mortality in certain species. As plants wilted and died, canopy cover decreased in wooded areas and the landscape generally became visibly brown, dusty, and harsh looking. Prolonged periods in which the landscape is visibly stressed are a disposition that can be traced to a time when rain-fed agriculture provided the major source of income and livelihood for rural families. The reduction and, in some cases, disappearance of plant cover exposed soils to the erosive force of winds and water [12].

Most farms at the time of the drought were (and still are) rain dependent. The number of irrigated farms was not known for the time. As a result, widespread crop failure was reported as a consequence of the drought [21]. Even for farms with access to potable water, rationing of supplies meant that priority for scarce water was given to hotels and households.

Sustainable agriculture integrates the three main goals of environmental health, economic profitability, and social and economic equity [17]. A variety of philosophies, policies, and practices have contributed to these goals. People in many different capacities, from farmers to consumers, have shared this vision and contributed to it. Despite the diversity of people and perspectives, the following themes commonly weave through definitions of sustainable agriculture. Sustainability rests on the principle that we must meet the needs of the present without compromising the ability of future generations to meet their own needs. Therefore, stewardship of both natural and human resources is of prime importance. Stewardship of human resources includes consideration of social responsibilities such as working and living conditions of laborers, the needs of rural communities, and consumer health and safety both in the present and the future. Stewardship of land and natural resources involves maintaining or enhancing this vital resource base for the long term.

15.3 Sustainable Farming Systems

Sustainable farms produce crops and raise animals without relying on toxic chemical pesticides, synthetic fertilizers, genetically modified seeds, or practices that degrade soil, water, or other natural resources. By growing a variety of plants and using techniques such as crop rotation, conservation tillage, and

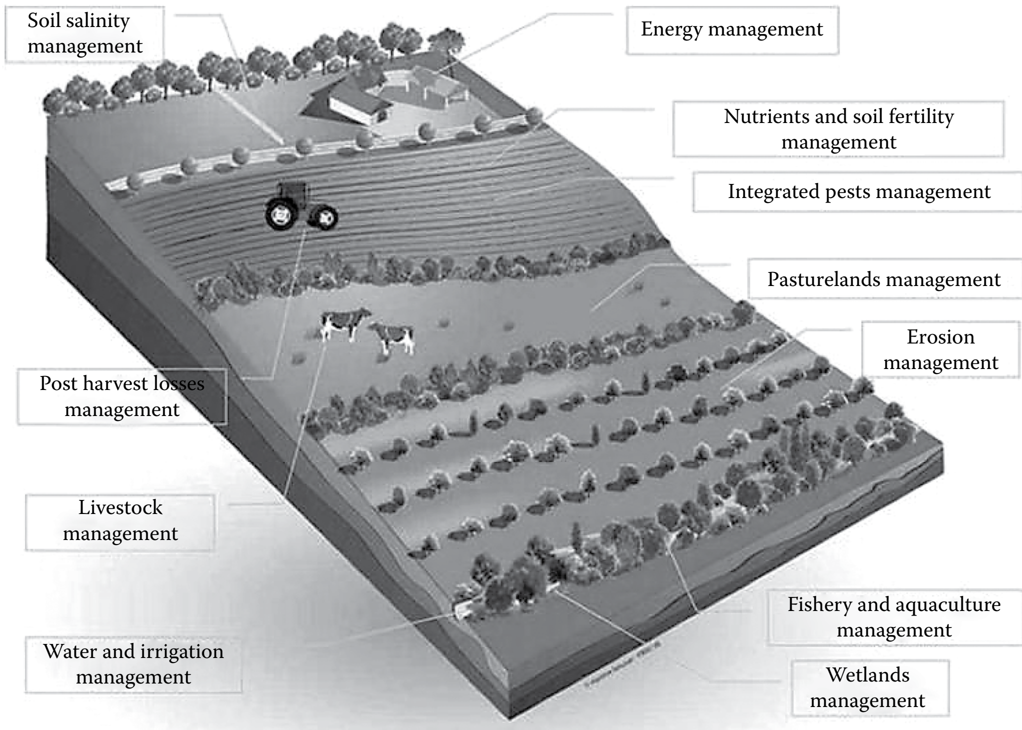

FIGURE 15.1 Sustainable farming practices.

pasture-based livestock husbandry, sustainable farms protect biodiversity and foster the development and maintenance of healthy ecosystems [20]. Figure 15.1 shows activities involved in sustainable farming systems.

Food production should never come at the expense of human health. Since sustainable crop farms avoid hazardous pesticides, they are able to grow fruits and vegetables that are safer for consumers, workers, and surrounding communities. Likewise, sustainable livestock farmers and ranchers raise animals without dangerous practices like use of nontherapeutic antibiotics or arsenic-based growth promoters. Through careful, responsible management of livestock waste, sustainable farmers also protect humans from exposure to pathogens, toxins, and other hazardous pollutants [17].

A critical component of sustainable agriculture is its ability to remain economically viable, providing farmers, farm workers, food processors, and others employed in the food system with a livable wage and safe, fair working conditions. Sustainable farms also bolster local and regional economies, creating good jobs and building strong communities. Sustainable management of water in agriculture is critical to increase agricultural production, ensure water can be shared with other users and maintain the environmental and social benefits of water systems. Agriculture needs, therefore, to use water in a more efficient way [3,14,21].

15.3.1 Sustainable Farming System Framework

Table 15.1 shows components of the sustainable farming system as a whole farm approach that provides a framework covering farm selection and management, integrated crop and pesticide management, soil protection, and yards (Table 15.1).

TABLE 15.1 Farm Selection and Management, Integrated Crop and Pesticide Management, Soil Protection, and Yards

Item	Principles and Recommended Practices
Farm selection and management	• When planning and managing the farm activities, properly take into account the farm specificities—such as availability and quality of water resources. • Be aware of the farm's characteristics (including surrounding water courses, the level of water stress, availability and quality of water resources, soil type) and based on these, choose the best location for crop production. Plan water harvesting and storage units if necessary. • Set a management plan for potential pollutants: Nutrient and pesticide management, erosion, animal feeding operations, grazing management, and irrigation water management.
Integrated crop management	• Use conservation agriculture techniques to minimize the delivery and transport of agriculturally derived pollutants to surface and groundwater. • To control diffuse pollution, conduct conservation practices to minimize pollutants, slow the transport and/or delivery of pollutants, either by reducing water transported, and thus the amount of the pollutant transported, or through deposition of the pollutant; or to remediate or intercept the pollutants to surface and groundwater. • Reduce pollutant before or after it is delivered to the water resource through chemical or biological transformation. • Conservation tillage can help reduce overland transport of nitrogen by reducing erosion and runoff, and nutrient management will minimize subsurface losses due to the resulting increased infiltration. Buffer strips can be used to decrease nitrogen transport by increasing infiltration, and through uptake of available nitrogen by the field border crop. Nitrogen not controlled by nutrient management, conservation tillage, and filter strips can be intercepted and remediated through denitrification in riparian buffers. • Establish conservation tillage buffer zones alongside watercourses. Extend existing buffers to gain more efficiency in intercepting overland flow and reducing the transport of nutrients, pesticides, and agrochemicals. Farming on the contour creates small ridges that slow runoff water. In strip cropping, the small grain or hay strips slow runoff water, allowing infiltration and filtering sediment.
Integrated pest management	• Utilize integrated pest management systems for prevention, avoidance, monitoring, and suppression techniques, and only apply the lowest-risk pesticides available in an environmentally sound manner when monitoring indicates that an economic pest threshold has been exceeded.
Soil protection	• Prevent surface water pollution by reducing soil erosion. • Reduce soil erosion and improve water infiltration by ploughing along contours and use conservational tillage where appropriate. • Block runoff pathways (relocate gates if applicable). Catch any surface runoff by establishing infield grass strips.
Yards	• Protect water quality by avoiding runoff and careful use of effluents. • Runoff liquid from manure from yards should be contained where pollution of water is a risk.

15.3.2 Economic Sustainability

A good management of water resources will help farmers to cut costs while maintaining or improving the productivity of the land and reduce the risk of pollution [22]. Table 15.2 provides some practices to ensure safety, quality and transparency, financial stability, accountability, innovation, and risk management from an economic perspective.

15.3.3 Social Sustainability

Achieving success in water conservation requires various levels of engagement and collaboration throughout the entire food sector and its stakeholders. Throughout this collaboration, it appears that several solutions exist to improve the water use at the farm level, including good practices [17]. From a social perspective, this section focuses on working conditions, capacity building, and community engagement and recommends some practices to ensure an adequate water management at a farm level (Table 15.3).

TABLE 15.2 Economic Sustainability

Item	Principles and Recommended Practices
Safety, quality, and transparency	• Ensure the safety, quality, and transparency of the water use throughout the farming production. • Ensure that the water-saving equipment reduces the demand for water.
Financial stability	• Seek to achieve income long-term stability of the farm for proper investments and adaptation investments, taking into account results linked to water use. • Assess a potential future cost of adapting to water scarcity—including energy prices, insurance, and credit costs. • Manage water application for maximum economic benefit with minimum impact on the environment.
Accountability	• Ensure the accountability and profitability of the farming system, taking into account results linked to water use. • Keeping a good accountability can help farmers to use water more efficiently, save cost, and reduce water consumption.
Innovation	• Encourage the use of Best Available Technologies or new innovative ideas that optimize water use. • Encourage innovation (this includes new ideas, technologies, methodologies, crop plan, processes, new markets, and new approaches to old markets). • Promote water efficiency and avoid water pollution.
Risk management	• Identify and assess economic risks linked to water use. • Assess the exposure to water risks and make this information available. • Understand how the amount and source of the water withdrawals and the quantity and quality of wastewater discharges impact local communities and ecosystems. • Assess the quantity/quality of the wastewater discharges in relation to permitted levels and/or industry averages.

TABLE 15.3 Social Sustainability

Item	Principles and Recommended Practices
Working conditions	• Ensure water access among workers. • Access to potable water and toilets should be guaranteed for all employees and workers. This equally refers to employees and workers as well as their families when living on the farm.
Capacity building	• Support the training of farm employees and workers and increase awareness on water use and management.
Community engagement	• Contribute to engage with the employees, workers, and local communities. • Understand any conflicting water use demands and the communities' dependency on water resources and/or conservation requirements that may exist in the area. • Establish an ongoing process for community relations management that directly addresses water issues. This could involve a designated contact person in the local community or a community relations department within the company.

15.3.4 Environmental Sustainability

Agriculture is considered to be a significant contributor of water pollution by nonpoint sources. Diffuse pollution can arise from a range of activities on the farm, such as the leaching of fertilizers or soil erosion, which are spread out over a wide area and therefore harder to pinpoint and control. Many of the substances used in agriculture that can cause water pollution (fertilizers, pesticides, manure and slurry, even the soil itself) are essential elements of farming. Wise stewardship of water resources can help ensure to diminish the effect of agriculture practices on quality and availability of water resources [21]. Delivering real benefits for farmers and the environment, while at the same time minimizing the effects on the environment, involves various aspects of environmental sustainability. This requires a close look at water for irrigation, leaks, pesticides management, water quality, water conservation practices, and the establishing of a comprehensive water management at a farm level (Table 15.4).

TABLE 15.4 Environmental Sustainability

Item	Principles and Recommended Practices
Irrigation	• Properly plan the irrigation system, if appropriate, and make sure it achieves water reduction. • Ensure the irrigation system in place, if any, is working properly. • Schedule irrigation to reduce water use, i.e., the crop's water requirements shall be systemically assessed in order to set the time and volume of crop irrigation. • Properly manage irrigation use. • Properly measure the irrigation system.
Leaks	• Prevent and reduce water losses. • Insulate pipes properly, lagging all exposed pipe work within 750 mm of ground level.
Pesticide management	• Ensure responsible and efficient use of pesticides and chemicals in the farm. • Ensure safe pesticide/fertilizer storage.
Water conservation	• Properly choose crops so they are as suitable as possible for the agro-climatic conditions. • Select crops compatible with water availability. • Minimize and/or reduce water use on the farm. • Good agricultural practices such as managing soil fertility and reducing land degradation can increase water efficiency.
Water quality	• Ensure quality of water is suitable for irrigation. • Complete an annual risk assessment for irrigation water pollution. The risk assessment must consider potential microbial, chemical, or physical pollution of all sources of irrigation water. • Minimize water pollution point and nonpoint water sources. • Seek professional advice in assessing and planning pollution control.
Water audit	• Conduct a water use inventory to manage and optimize water use in farm. • Conduct a water audit and a water balance for the farm.
Water management	• Minimize impacts on water courses and the environment. • Develop, implement, and manage and monitor a comprehensive water management. • Plan for the whole farm.

15.4 Types of Sustainable Farming Practices

Sustainable production practices involve a variety of approaches. Specific strategies must take into account topography, soil characteristics, climate, pests, local availability of inputs, and the individual grower's goals [3]. Despite the site-specific and individual nature of sustainable agriculture, several general principles can be applied to help growers select appropriate management practices.

15.4.1 Conservation Agriculture

Conservation agriculture (CA) is any tillage sequence that minimizes or reduces the loss of soil and water. In the drylands, CA has been loosely applied to any tillage system whose objective is to conserve or reduce soil, water, and nutrient loss, or which reduces draft power (human, animal, and mechanical) input requirements for crop production [16]. Operationally, it is tillage or combined tillage and planting that leave 30% or more mulch or crop cover on the surface [10]. Thus, CA is a generic term used to categorize a set of farming practices designed to increase the sustainability of food and fiber production by conserving soil, water, and energy resources. It encompasses activities such as minimum tillage and zero tillage; tractor powered, animal powered, and manual methods; integrated pest management; integrated soil and water management, including conservation farming. CA is contrasted to conventional agriculture in which a primary inversion tillage operation (ploughing) followed by tilth conditioning operations (discing, harrowing, and rotovating) are used to prepare the seedbed before planting by loosening the root zone soil, burying crop residues, and removing existing weeds.

Conceptually, CA has evolved from an initial preoccupation with a reduction or elimination of inversion tillage as reflected in erstwhile terminology such as reduced tillage, zero tillage, and stubble-mulch tillage to a generic concept that combines a package of four cardinal principles. These key tenets of the CA include the reduction or elimination of soil disturbance by adopting reduced or zero tillage techniques, the maintenance of soil cover with live crops or crop residues, the use of crop rotations or cover crops, and the enhanced levels of management that include timeliness (planting at the earliest planting opportunity and weeding as soon as weeds emerge), precision (precise placement of seed and fertilizer/manure into permanent planting basins or rip lines), and thoroughness (keeping the crop weed-free throughout the season and dry season weed control to reduce weed seed numbers in the soil seed bank).

15.4.2 Conservation Farming

Conservation farming (CF) is increasingly gaining recognition in semiarid regions as a group of technology interventions that have the potential to sustainable increase yields from a wide range of crops through the conservation of soil, water, nutrients, and farm power. CF is the particular technology using planting basins and soil cover. This is a modification of the traditional pit systems once common in southern Africa and is a variation on the *Zai* pit system from West Africa, which may also be considered a CF technology [1]. The following are components of CF: preparing basins, basal manure application, topdressing with nitrogen fertilizer, crop residue application, basal inorganic fertilizer, crop rotation, and timely post-planting weeding. Thus, conservation farming is part of a growing group of conservation agriculture techniques, which cover a wide range of minimum or zero tillage systems and integrated pest, soil, and water management practices.

It is important to note that conventional farming and conservation agriculture are different farming practices. The two include a very wide range of operations: field preparation, planting, fertilization, weeding, harvesting, and field operations after the harvest. Conservation agriculture and conservation farming are not the only types of sustainable agriculture and resource management. They overlap with various other approaches.

15.4.3 Sustainable Land Management

Sustainable land management or land husbandry is a broad term that includes various types of crop and livestock production that aim to produce good yields year after year, while conserving soil and water resources. It does not necessarily include all three principles of conservation agriculture, namely, not turning the soil, keeping the soil covered, and rotating crops. Conservation agriculture is a type of sustainable land management [22].

15.4.4 Organic Farming

This involves the growing crops and livestock without using agrochemicals. It is possible to do conservation agriculture in an organic way without using fertilizers, herbicides, or pesticides. However, many types of conservation agriculture practices use agrochemicals, though in small amounts and with care.

15.4.5 Agroforestry

This is a combination of trees and crops or livestock and is a form of sustainable land management. Agroforestry promotes soil cover and crop rotation, hence contributing to a conservation agriculture system.

15.5 Water Management in Sustainable Agriculture

Agriculture is a major user of water resources and also contributes to water pollution from excess nutrients, pesticides, and other pollutants [23]. But the competition for water is increasing and the costs of water pollution can be high. Farming accounts for around 70% of water used in the world today [7].

Climate change could affect water supply and agriculture through changes in the seasonal timing of rainfall and snow pack melt, as well as higher incidence and severity of floods and droughts.

15.5.1 Water Use for Specific Crops

This involves a set of principles and practices for sustainable water management for some specific agriculture production. Selection of species and varieties that are well suited to the site and to conditions on the farm is required [14]:

- Diversification of crops (including livestock) and cultural practices to enhance the biological and economic stability of the farm
- Management of the soil to enhance and protect soil quality
- Efficient and humane use of inputs
- Consideration of farmers' goals and lifestyle choices. Table 15.5 shows principles and practices for coffee, dairy and livestock, and vegetables and fruits production in sustainable systems.

Challenges of CA include [14]

- Labor-intensive—many operations required, winter management
- Protecting plots from livestock
- Stover-livestock feed competition
- Termites damage stover
- Institutional restrictions—plot size
- Local fertilizer shortage
- Rotation—difficult to access legume seed

Conservation tillage, therefore, takes care of this by applying four main principles: (1) zero or minimum soil turning, (2) permanent soil cover, (3) stubble-mulch tillage, and (4) crop selection and rotations. An important aspect of conservation tillage practice involves ripping the land with tined implements or subsoiling the land immediately after crops are harvested to break the plough pans. Suitable equipment includes animal-drawn subsoilers, rippers, ridgers, planters, and weeders [1,2,5].

CA techniques have been evaluated and actively promoted in Zimbabwe since the 1980s: no-till tied ridging; mulch ripping; no-till strip cropping; clean ripping; hand-hoeing or zero till; tied furrows (for semiarid regions) and open plough furrow planting, followed by mid-season tied ridging. These have frequently been promoted in combination with mechanical structures such as [1] graded contour ridges;

TABLE 15.5 Principles for Coffee, Dairy and Livestock, and Vegetables and Fruits Production

Item	Principles and Recommended Practices
Coffee	• Properly manage and optimize water use. • Minimize the volume of water used to irrigate plantations by using drip irrigation as it has the advantage of not causing erosion on steep sites. Sprinkler. • Reduce the volume of water used in wet processing of coffee via the application of efficient technologies and recycling of water.
Dairy and livestock	• Protect water courses. • Minimize and reduce water spillage and contamination. • Provide sufficient and clean water to animals. • Seek efficient water use and reuse water whenever possible. • Minimize and/or reduce water use for drinking.
Vegetables and fruits	• Minimize and/or reduce water use in vegetable and fruit production. • Reduce the amount of waste generated and therefore its water embeddedness. • Minimize and/or reduce water use in cleaning and washing. • Reuse water from fruit and vegetable processing.

dead level contour ridges with crossties (mainly for semiarid regions); infiltration pits dug at intervals along contour ridge channels; *fanya juus* (for water retention in semiarid regions); vetiver strips and broad-based contour ridges (mainly used on commercial farms).

15.5.2 Minimum Mechanical Soil Disturbance

Conventionally, tillage is conducted to prepare a seedbed and also to control weeds. However, conventional tillage has been found to destroy the structure of the soil and cause compaction. This has negative effects on soil aeration, root development, and water infiltration among other factors. More important, but less noticeable, is the destruction of soil microbiology by disturbance and turning over of soil, which is then exposed to drastic atmospheric and climatic conditions [10,13].

In its extreme form, minimum tillage includes zero tillage, and/or no-till subsystems where the land is planted by direct seed drilling without opening any furrows or pits. Minimum tillage is essential in maintaining minerals within the soil, stopping erosion, and preventing water loss from occurring within the soil. In the past, agriculture has looked at soil tillage as a main process in the introduction of new crops to an area. It was believed that tilling the soil would increase fertility within the soil through mineralization that takes place in the soil. Also, tilling of soil can cause severe erosion and crusting, which will lead to a decrease in soil fertility. Today, tillage is seen as a way of destroying organic matter provided within the soil cover. No-till farming has caught on as a process that can save soil organic levels for a longer period and still allow the soil to be productive for longer periods [9]. The process of tilling increases the time and labor for producing a crop. When no-till practices are followed, the producer sees a reduction in production cost for a certain crop. Tillage of the ground required more money due to cost of fuel for tractors or feed for the animals pulling the plough. The producer sees a reduction in labor because he or she does not have to be in the fields as long as a conventional farmer.

15.5.3 Crop Rotations

This is the practice of crop rotation with more than two species. Crop rotation can be used best as a disease control against other preferred crops. This process will not allow pests such as insects and weeds to be set into a rotation with specific crops. Rotational crops will act as a natural insecticide and herbicide against specific crops. Not allowing insects or weeds to establish a pattern will help to eliminate problems with yield reduction and infestations within fields [7,8]. Crop rotation can also help build up a soil's infrastructure [19]. Establishing crops in a rotation allows for an extensive buildup of rooting zones, which will allow for better water infiltration Table 15.6 shows crop rotations recommended for agro-ecological regions in Zimbabwe.

15.5.4 Digging Planting Basins

Planting basins are simple pits or holes that can be dug with hand hoes without having to plough the whole field. They are dug in a weed-free field into which a crop is planted. Planting basins capture rainwater.

TABLE 15.6 Crop Rotations Recommended for Agro-Ecological Regions in Zimbabwe

Region	Rainfall (mm)	Rainfall Characteristics	Crop Area (ha)	Crops/Rotation
11	650–800	Good distribution	3 × 0.25	Maize cotton-legume (groundnuts/soybean)
111	650	30–40 rain days		Maize cotton-legume (groundnuts/cowpea/soybean)
iv	500–650	30 rain days		Maize/sorghum/pearl millet
				Groundnuts/cowpea/sunflower/cotton
v	Less than 500	16–30 rain days		Sorghum/pearl millet/maize
				Groundnuts/cowpea

The basins are prepared in the dry season from July to October in Zimbabwe. The recommended dimensions of the basin are 15 cm × 15 cm × 15 cm, spaced at either 75 × 60 cm for the less dry regions and either 75 cm × 75 cm or 90 cm × 60 cm for dry regions. The basins enable the farmer to plant the crop after the first effective rains when the basins have captured rainwater and drained naturally. Seeds are placed in each basin at the appropriate seeding rate and covered with clod-free soil. The advantage of using basins is that they enhance the capture of water from the first rains of the wet season and enable precision application of both organic and inorganic fertilizer as it is applied directly into the pit and not broadcast [15].

15.5.5 Permanent Soil Cover

A permanent year-round soil cover using cover crops and mulch is central to conservation agriculture. It protects the soil from rain, wind, and sun, thereby reducing erosion and increasing soil moisture; it suppresses weeds and enhances soil fertility and the organic matter content [16]. There are two main types of soil cover: living plant material (crops and cover crops) and mulch or dead plant material (crop residues and prunings from trees and shrubs).

Crop residue left on the surface shields the soil from rain and wind until emerging plants provide a protective canopy. Crop residue also improves soil tilth and adds organic matter to the soil. It is associated with reduced tillage, which limits soil compaction and saves the farmer time and fuel [21].

Mulching with the previous season's stover provides weed control throughout the year. The layer of mulch that is built up over time will start to become like a buffer zone between soil and mulch, which will help reduce wind and water erosion [11]. With this comes the protection of a soil's surface when rain is falling to the ground. Rainfall on land that is not protected by a layer of mulch is left open to the elements. But when soils are covered under a layer of mulch, the ground is protected so that it is not directly impacted by rainfall. This type of ground cover also helps keep the temperature and moisture levels of the soil at a higher level than if it was tilled every year [9].

The use of basal fertilizer amendments either manure or compound fertilizers, followed by microdosing topdressing fertilizer, is recommended [18]. The most commonly implemented techniques are crop residue application, basal fertilizer application, and crop rotation. Conservation agriculture means less work as it is not necessary to plough the soil and weed as many times. It suppresses weeds, reduces erosion, and improves the soil structure, hence its ability to retain water, organic matter content, and fertility. All these lead to higher and more stable yields than conventional tillage.

15.5.6 Diversity

Diversified farms are economically and ecologically resilient. While monoculture farming has advantages in terms of efficiency and ease of management, the loss of the crop in any one year could put a farm out of business and/or seriously disrupt the stability of a community dependent on that crop. By growing a variety of crops, farmers spread economic risk and are less susceptible to the radical price fluctuations associated with changes in supply and demand. Properly managed, diversity can also buffer a farm in a biological sense. For example, in annual cropping systems, crop rotation can be used to suppress weeds, pathogens, and insect pests [8]. Also, cover crops can have stabilizing effects on the agro-ecosystem by holding soil and nutrients in place, conserving soil moisture with mowed or standing dead mulches, and by increasing the water infiltration rate and soil water holding capacity. Cover crops in orchards and vineyards can buffer the system against pest infestations by increasing beneficial arthropod populations and can therefore reduce the need for chemical inputs. Using a variety of cover crops is also important in order to protect against the failure of a particular species to grow and to attract and sustain a wide range of beneficial arthropods [22].

Optimum diversity may be obtained by integrating both crops and livestock in the same farming operation. This was the common practice for centuries until the mid-1900s when technology, government policy, and economics compelled farms to become more specialized. Mixed crop and livestock operations have several advantages [22]. First, growing row crops only on more level land and pasture or forages on steeper slopes will reduce soil erosion. Second, pasture and forage crops in rotation enhance soil quality and reduce erosion; livestock manure, in turn, contributes to soil fertility. Third, livestock can buffer the negative impacts of low rainfall periods by consuming crop residue that in "plant only" systems would have been considered crop failures. Finally, feeding and marketing are flexible in animal production systems. This can help cushion farmers against trade and price fluctuations and, in conjunction with cropping operations, make more efficient use of farm labor.

15.6 Summary and Conclusions

Sustainable agriculture is the production of food, fiber, or other plant or animal products using farming techniques that protect the environment, public health, human communities, and animal welfare. This form of agriculture enables us to produce healthful food without compromising future generations' ability to do the same. The primary benefits of sustainable agriculture are environmental preservation, protection of public health, sustaining vibrant communities, and upholding animal welfare.

Effective rainfall management in sustainable agriculture aims to produce high crop yields while reducing production costs, maintaining the soil fertility, and conserving water. It is a way to achieve sustainable agriculture and improve livelihoods by applying the basic principles: disturb the soil as little as possible; keep the soil covered as much as possible; and mix and rotate crops.

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16

Deficit Irrigation: Farmlands

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Abstract Lack of water is one of the biggest challenges to implementing sustainable development, especially in the agricultural sector. If appropriate strategies are not adopted for water resource management, it will be difficult for societies to create an adequate food supply. Despite limited water resources in many areas of the world, irrigation practices still disregard principles of resource conservation and sustainability, and practices of irrigation management need to maximize efficiency. Water consumption savings can be realized by changes in irrigation management and agriculture. In this chapter, we study the use of the deficit irrigation technique as an effective method for irrigation management, one that justifies and determines minimum water consumption with acceptable and economic performance. This chapter focuses on theoretical and practical analysis of the use of the deficit irrigation method for irrigation scheduling. We hope the contents of this chapter play a role in improving water resource management in agriculture.

16.1 Introduction

Due to population growth and increasing demand for fresh water in municipal, industrial, agricultural and environmental sectors, a future reduction in the quantity and quality of water, especially in arid and semiarid regions, is predicted on a global scale. So, the world's biggest water problem is an uncertain water supply for the generations to come [21]. But even in the current situation, the water crisis in some communities is dire enough to warrant sewage reuse in order to meet certain public use requirements [30]. Agriculture is the main consumer of water in the world, especially in arid and semiarid regions; growing demand for food, as well as dietary changes, has water resource planners specifically considering irrigation to ensure a sufficient food supply [13]. Irrigation prevents water shortages and low crop production; these shortages are due to (1) water lost through evaporation from the soil surface and transpiration from plants, called "evapotranspiration" (ET); (2) water losses caused by percolation in agriculture land. Irrigation techniques maximize water productivity by reducing evaporation and transpiration. Yet, yield loss from reduction of ET is inevitable because plant transpiration is coupled with carbon capture for photosynthesis [28,37,41]. The irrigation deficit concept goes back to 1970s, but by the 1990s, the literature on the design of irrigation systems proposed an operation of these systems that failed to provide a sufficient water supply and that rejected deficit irrigation to achieve maximum yield [15]. This approach was increasingly challenged by different sectors of society that faced water scarcity, especially those communities where drinking and industrial water supply were limited, due to excess water use in irrigation. Furthermore, excessive water extraction has had negative effects on nature and some considerable research was directed toward deficit irrigation. However, progress in these types of research was slow and faced with many barriers [5,17]. Allocation of agriculture water is influenced by the maximum ET under deficit irrigation which is covered by stored water, more cultivated area with less irrigation or replaced by other applications. Deficit irrigation could yield economic benefits under appropriate circumstances, depending on the interaction of various and effective measures such as crop price, water price, and the cost of production. Although a direct result of deficit irrigation is yield loss per unit area, reducing production costs and optimizing net profit or the benefit–cost ratio compensates for this yield loss. Many studies have been conducted by different researchers on the advantages of deficit irrigation [4,8,29,39,44]. In 1996, English and Raja investigated the benefits of deficit irrigation in the northwestern United States for wheat, in California for cotton, and in Zimbabwe for corn [16]. The results of their study showed that the optimal deficit irrigation of 15%–59% for these crops would lead to a maximum net profit in the regions mentioned. In another study, conducted in Botswana, the maximum net profit for broccoli and carrots was achieved at 20% deficit irrigation [20]. Also Sepaskhah and Ghahreman [33] during a study in Iran showed that an optimum net profit for barley, sorghum, and corn could be achieved at the 60% irrigation level. Romero et al. [32] researching in Spain showed that a 45% lower water application (deficit irrigation) in almond orchards led to 17% loss in agricultural crops. Shahnazari et al. [35] carried out a survey in Iran that showed deficit irrigation would not significantly reduce crop loss by using 70%–90% of the water requirement during periods insensitive to water stress. Banihabib et al. [2] evaluated the effect of irrigation water subsidies on net income and the percentage of optimal deficit irrigation by providing an integrated model of uniform deficit irrigation for the cropping pattern of wheat and tomato. Deficit irrigation is also very important for planning water distribution of agricultural reservoirs; it can be done by releasing water from the reservoir based on optimal deficit irrigation at different growth stages; or it is effective in optimization of reservoir management by defining parameters such as maximum seasonal shortage [3,45].

An important hurdle in the implementation and operation of deficit irrigation on farms is convincing farmers to practice the method not only for its economic value but also for its practicality [6,23].

16.2 Definition of Deficit Irrigation

Deficit irrigation is a type of agricultural water management.In this method, plants are aggregated due to the water supply in the soil and rainfall to some extent, which less than 100% of the water requirement reach the plant by evapotranspiration. This allows water requirements to increase water supply for other uses. Deficit irrigation is also referred to by different names, including limited irrigation, partial irrigation, regulated deficit irrigation, and ET deficit irrigation [15]. Because of the cost of water and water supply reduction in terms of deficit irrigation, producers were led to this type of management, which differs from full irrigation. In the context of deficit irrigation management, different levels of water stress in plants are inevitable. But the challenge defined in this management is to minimize the negative effects of stress. In this type of management, proper choice of timing and amount of irrigation is essential for optimizing duration and degree of stress the plant experiences during water restrictions. In the other words, deficit irrigation is a simple management technique to achieve economic optimization during water restrictions and imposes a significant number of adjustments in the agricultural system by reducing water supply. The management of a deficit irrigation system is based on a mathematical functions of crop production. The optimal depth of irrigation is discovered through economic analysis assisted by these functions. In this way, various economic indicators are optimized by deficit irrigation, depending on the goals of agricultural system.

16.3 Functions of Crop Production

Crop production functions have been suggested in several studies to analyze deficit irrigation; they include crop production functions in terms of irrigation water depth and evapotranspiration. Crop production as a function of irrigation water depth is a nonlinear, usually quadratic, polynomial, whereas crop production function in terms of evapotranspiration is linear. It should be noted that nonlinear and linear production functions are, respectively, provided by English et al. [15] and Stewart et al. [40].

16.4 Nonlinear Function and Optimum Points

Revenue from agricultural land is based on crop yield and crop price; Equation 16.1 shows the revenue function:

$$R(w) = P_c y(w), \tag{16.1}$$

where
- $R(w)$ is the revenue per hectare
- $y(w)$ is the crop production function
- w is the depth of irrigation water.

The relationship between the depth of irrigation water (w) and crop yield (y) is generally presented as a quadratic equation (Equation 16.2):

$$y(w) = a_1 + b_1 w + c_1 w^2 \tag{16.2}$$

The straight line in Figure 16.1 represents a function of total production costs (c) to applied water; the y-axis intercept is related to fixed costs (costs of tillage, planting, and harvesting), while the slope shows the variable costs (such as water costs, pumping costs, labor, and maintenance). The cost equation based on irrigation depth is represented in the following equation.

$$C(w) = a_2 + b_2 w \tag{16.3}$$

According to studies by English [14], the five optimum levels of applied water can be measured, providing the maximum profit and yield per unit of water or land with a limited availability of resources. w_m is the level of deficit irrigation at which crop yield per unit of land is maximized. The level at which net income per unit of land is maximized is given as w_e. The level of deficit irrigation at which net income per unit of water is maximized is w_w. Also, w_{el} and w_{ew} are the levels at which net income equals that at full irrigation when land or water are respectively limiting. Equation 16.4 calculates the w_m level:

$$w_m = -\frac{b_1}{2c_1} \tag{16.4}$$

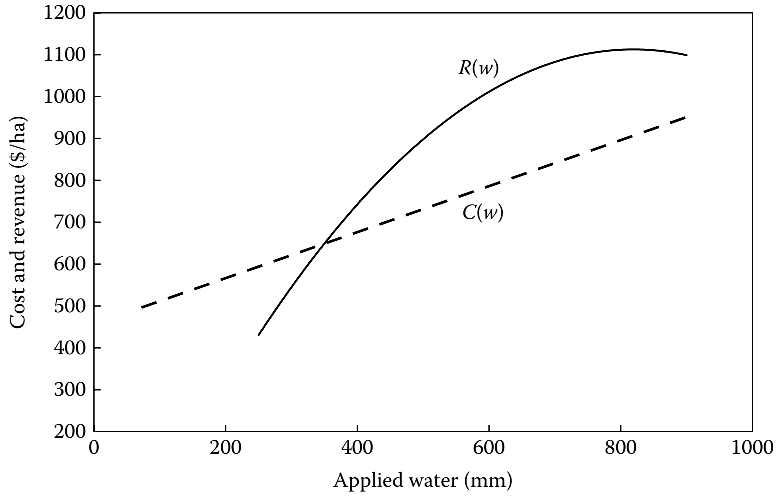

FIGURE 16.1 Revenue and cost function.

Equation 16.5 evaluates the w_l level:

$$w_l = \frac{b_2 - p_C b_1}{2 p_C c_1} \tag{16.5}$$

Equation 16.6 calculates the w_m level:

$$w_m = \left(\frac{p_C a_1 - a_2}{p_C C_1} \right)^{1/2} \tag{16.6}$$

Equations 16.7 and 16.8 estimate the level of w_{el}:

$$w_{el} = \frac{b_2 - p_C b_1 + Z_1}{2 p_C c_1} \tag{16.7}$$

$$Z_1 = \left[\left(P_c b_1 - b_2 \right)^2 - 4 P_C c_1 \left(\frac{p_C b_1{}^2}{4_{c1}} - \frac{b_1 b_2}{2 c_1} \right) \right]^{1/2} \tag{16.8}$$

Finally, Equations 16.9 and 16.10 estimate w_{ew} level:

$$w_{ew} = \frac{-Z_2 + \left[Z_2^2 - 4 P_C C_1 \left(P_C a_1 - a_2 \right) \right]^{1/2}}{2 P_C C_1} \tag{16.9}$$

$$Z_2 = \frac{P_C b_1^2 - 4 a_2 c_1 + 4 P_C a_1 c_1}{2 b_1} \tag{16.10}$$

TABLE 16.1 Optimum Levels of Applied Water in Oregon Region

	Water Use		Net Returns		Profit Increase at Optimum	
	Applied (cm)	Deficit (%)	To Land ($\$ha^{-1}$)	To Water ($\$m^{-3}$)	Land Limiting (%)	Water Limiting (%)
w_m	61	—	453.70			
w_l	51	16	491.51	0.0964	8.3	
w_w	37	39	414.81	0.1110		49
w_{el}	42	31	453.7	0.1080		
w_{ew}	23	62	170.90	0.0745		

Source: English, M.J. and Raja, S.N. 1996. Perspective on deficit irrigation. *Agricultural Water Management*, 32: 1–14.

Example

A farm is located in the Columbia Basin, in eastern Oregon, an arid region facing water scarcity. The crop is winter wheat, for which the crop yield function and cost function are respectively presented in the following equations:

$$y(w) = -0.5348 + 0.3326w - 0.00273w^2 \tag{16.11}$$

$$c(w) = 482.3 + 7.79w \tag{16.12}$$

In these equations, irrigation depth is expressed in cm, crop yield in kg ha^{-1} and cost as U.S. dollars. Also, the price of wheat harvested is assumed to be \$147 per metric ton. The optimum levels of applied water in this region are shown in Table 16.1 [16].

16.5 Deficit Irrigation at Different Growth Stages

If water stress is experienced at certain growth stages, the curve changes the production function. For example, corn growth stages are divided into three parts including (1) foliage growth, (2) flowering, and (3) seed ripening. Production functions for deficit irrigation are provided for any of the above and in uniform deficit irrigation at all growth stages in Figure 16.2. Based on the figure, deficit irrigation for *III* condition is applied uniformly at all stages of growth, *OII* only in the first stage of growth, *IOI* in the second stage, and *OOI* condition is applied in the first and second stages of growth.

16.6 Limitations of Yield Function Curves

A point that should be considered is the limitation of the equations. These equations are valid only in the domain that deficit irrigation experiments were carried out, and the curves cannot be extended to forecast yield for nontested values. In addition, each crop and each variety has its own function in any climatic conditions, and yield function will be changed by variation in crop variety or weather conditions. Also, in the above equation, it has been supposed that deficit irrigation is applied uniformly during the growth season not only at the special stage of growth.

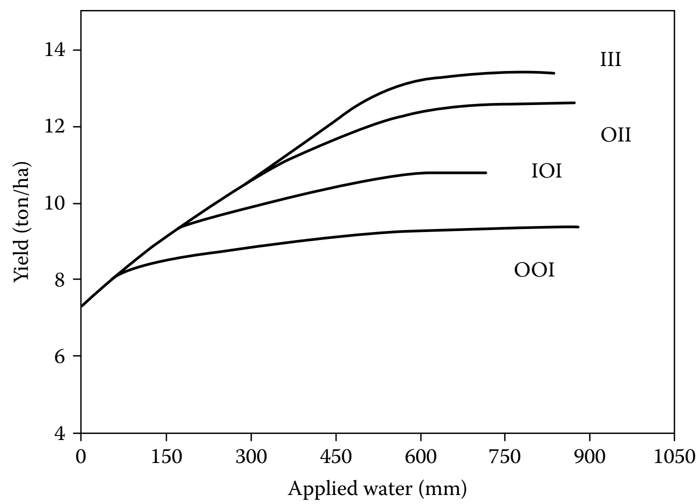

FIGURE 16.2 Corn yield curve by applying water stress at different stages.

16.7 Linear Yield Function

Stewart et al. [40] proposed a linear relation between relative evapotranspiration deficit and relative yield loss with slope equal to yield response factor:

$$\frac{y}{y_{\max}} = 1 - K_y\left[1 - \frac{ET_a}{ET_m}\right] \tag{16.13}$$

In this equation, y and y_{max} are, respectively, actual and maximum yield corresponding to ET_a and ET_m, respectively, the actual and potential (maximum) evapotranspiration. Also, K_y is yield response factor, which depends on irrigation system, irrigation management, plant variety, and the stage of growth at which deficit irrigation is applied.

For example, according to research of Calvache and Richardt in 1999 [7], the yield response factor of beans to deficit irrigation is different at different growth stages and in two types of irrigation system (Table 16.2). A K_y value greater than 1 shows crops are sensitive to deficit irrigation and relative yield reduction is higher than the water deficit caused by water stress; a K_y less than 1 shows crops are tolerant to deficit irrigation and the relative yield loss is less than the water deficit caused by water stress. If K_y equals 1, relative yield loss will be compensated by water deficit. Values of K_y are presented in Table 16.3 in uniform deficit irrigation at all growth stages for some crops. These results are based on a 4-year study of FAO in different parts of the world. K_y depends on climatic conditions, agriculture and irrigation management, and crop type and must be determined by field trials in any studies. Figure 16.3 shows variations of relative maize yield loss compared to the relative evapotranspiration deficit regarding K_y variations at different growth stages [38].

TABLE 16.2 Variation of Yield Response Factor of Beans to Deficit Irrigation at Different Growth Stages and Various Irrigation Systems

Crop	Specific Growth Stage	K_y	Irrigation Method
Common bean	Vegetative	0.57	Furrow
	Yield information	0.87	Furrow
	Whole season	0.99	Sprinkler

TABLE 16.3 K_y (Yield Response Factor) Values for Some Agricultural Crops

Crop	K_y	Crop	K_y
Alfalfa	1.1	Safflower	0.8
Banana	1.2–1.35	Sorghum	0.9
Beans	1.15	Soybean	0.85
Cabbage	0.95	Spring wheat	1.15
Cotton	0.85	Sugar beet	1
Groundnuts	0.7	Sugar cane	1.2
Maize	1.25	Sun flower	0.95
Onion	1.1	Tomato	1.05
Peas	1.15	Water melon	1.1
Pepper	1.1	Winter wheat	1.05
Potato	1.1		

Source: Doorenbos, J. and Kasssam, A.H., Yield response to Water, FAO Irrigation and Drainage Paper No. 33, FAO, Rome, Italy, 1979.

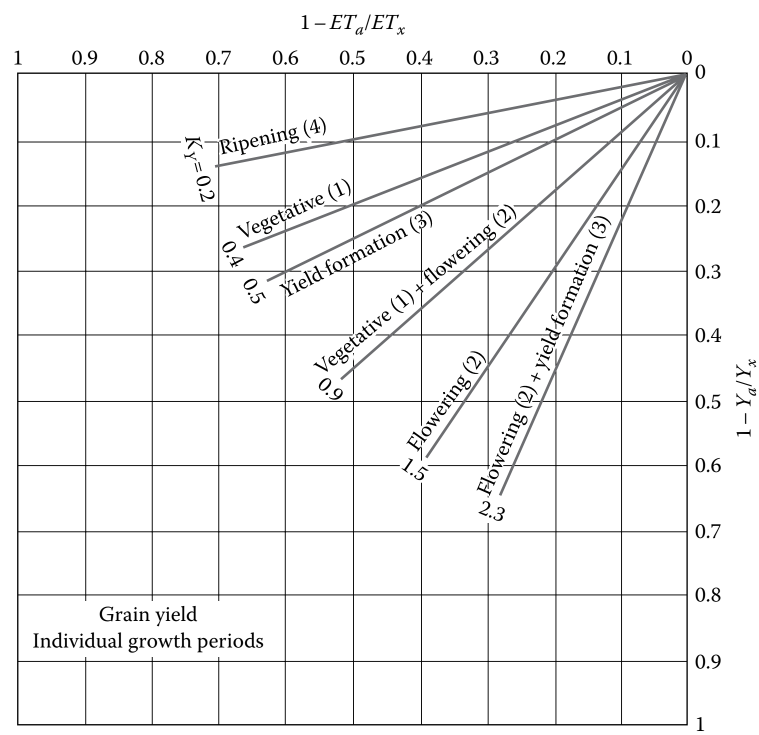

FIGURE 16.3 Linear water production functions for maize subjected to water deficits occurring during the vegetative, flowering, yield formation and ripening periods.

16.8 Nonuniform Deficit Irrigation at Different Growth Stages

Linear equation (16.13) will be used if deficit irrigation is applied uniformly at all stages of plant growth or only in one or more special stages of growth. Due to different sensitivities of plants to deficit irrigation at different growth stages, less deficit irrigation in more sensitive stages to water stress and higher deficit irrigation in less sensitive stages to water stress may produce better management results. Rao et al. [31] suggested a multiplicative equation for nonuniform irrigation at the different growth stages. In the previous equation, *i* is an index for plant growth stage and *n* is total number of growth stages.

$$\frac{y}{y_{max}} = \prod_{i=1}^{n}\left(1 - K_{y_i}\left(1 - \frac{ET_a}{ET_m}\right)_i\right) \tag{16.14}$$

Banihabib et al. [3] compared nonuniform and uniform deficit irrigation in downstream lands of a dam by providing a dynamic programming model for irrigation reservoirs. They showed nonuniform deficit irrigation has increased the land under cultivation by 48%, gross revenue by 47% and resulted in a higher benefit–cost ratio of 2.4% compared to uniform deficit irrigation.

16.9 Partial Root Zone Drying

Partial root drying (PRD) is a new deficit irrigation technique that improves water use efficiency without significantly reducing crop yield. This method was first considered for controlling additional foliage growth.

In PRD, the root zone is alternately irrigated and dried. In this technique, that part of the root zone which is fully irrigated absorbs sufficient water and the plant continues to grow. But in the part that is contact with the dry soil responds to drying by signals passed from the roots to the leaves, resulting in stomatal closure and reducing water use. Researchers believe that a crop's response to drying is due to abscisic acid (ABA) being discharged from the root [9,22].

During exposure of plants to water stress, this acid is synthesized by the roots and transported to the leaves and photosynthetic organs in the transpiration stream. Water loss is then minimized by reduction of the effective factors in photosynthesis; the most important of them are deceleration of leaf growth and decreasing stomatal aperture [10]. Much research has been done on deficit irrigation by the PRD method and associated effects on water use efficiency and crop yield [12,26,27]. Also, different studies of the significant effects of partial root-zone irrigation on crop quality have shown that this method improves crop quality, especially for fruits and vegetables [24,34,36,43]. For example, Tesfaye et al. [42] showed water use efficiency of 21%–43% has increased as compared to common methods of deficit irrigation and full irrigation by applying the PRD technique on coffee plant by 50%. Shahnazari et al. [34] showed that applying PRD on potato produced significantly increased crop marketable yield compared to full irrigation.

16.10 Effect of Deficit Irrigation on Water Productivity

Water productivity in irrigation is calculated as the ratio between the yield or net income per unit of water used in evapotranspiration. Productivity index is also used to analyze the amount of water applied for irrigation and to measure irrigation quality [1]. In the water-limiting case, the goals of farmers will be the maximization of profit per unit of applied water rather than maximization of profit per unit area, which is defined as water productivity (WP). Application of deficit irrigation management results in maximizing water productivity [25], which depends on the level of deficit irrigation. The relationship between crop yield and irrigation water or ET is shown in Figure 16.4. As can be seen in the figure, lesser depths of irrigation linearly increase evapotranspiration values, but at the greater

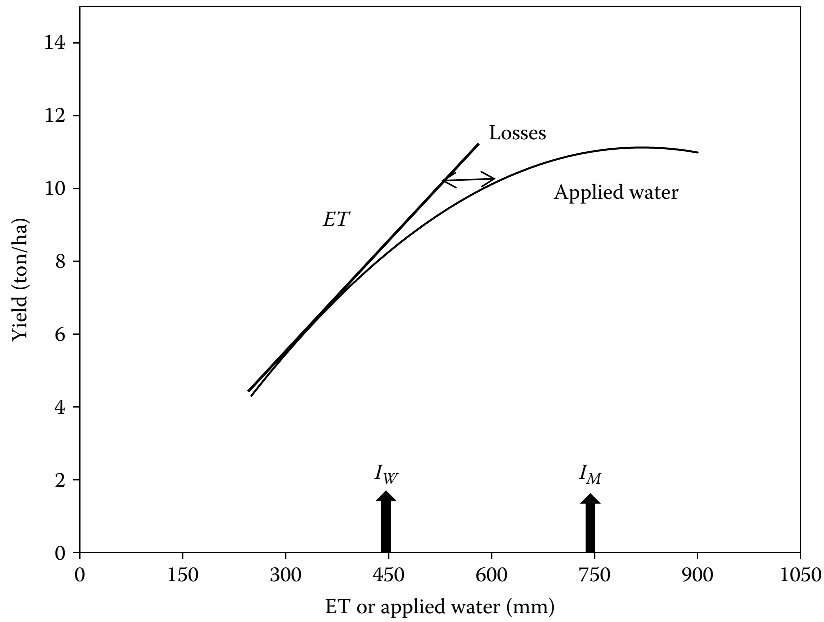

FIGURE 16.4 Generalized relationships between applied irrigation water, ET, and crop grain yield.

depths, a nonlinear relationship is seen and irrigation water is lost gradually. Based on Figure 16.4, I_W is the point beyond which water productivity starts to decrease while I_M shows the point beyond which the yield does not increase further with additional water irrigation [18]. However, if relative yield loss is less than relative *ET*, productivity under deficit irrigation to full irrigation will increase.

16.11 Farm Management Under Deficit Irrigation

Choice of proper plant species, soil conditions, and amount and frequency of water irrigation that should be used in deficit irrigation planning for cropping pattern are the most important factors determining the management and planning of deficit irrigation. Plants chosen for deficit irrigation should be resistant to water stress. High yielding varieties are usually not suitable for irrigation. For example, although high yielding varieties of corn produce more crops in full irrigation, their yield reduction is higher than low yielding varieties under deficit irrigation. The soil should have high depth, high moisture storage capacity, and low salinity and alkalinity to maintain the plant's water requirement even at high frequencies of deficit irrigation. Moisture stress in shallow and light textured soils is quickly developed and may a cause serious damage to plants, but deep soil due to high capacity loses moisture slowly, resulting in gradual expansion of moisture stress, and the plant is able to adjust cell sap to stresses. In addition to the benefits mentioned earlier, deep soils with high moisture content can absorb probable precipitation during growth period and apply it to the plant. Planning of deficit irrigation usually occurs with a change in the cultivation management. These changes include the following:

- Avoiding application of high plant density per unit area of land. The plant should have a lower density per unit area of land under deficit irrigation for efficient use of limited water; plant competition for water use is thus reduced
- Lower use of chemical fertilizers and pesticides
- Use of varieties that have a short growing season
- Use of the crop rotation and fallow for rainwater conservation
- Use of transplanting to prevent excessive consumption of water in early stages of growth.

16.12 Advantages and Limitations of Deficit Irrigation

There are several major advantages of deficit irrigation. They include the following:

- Improving water productivity and crop production.
  Maximizing water productivity by deficit irrigation is often more beneficial rather than maximizing crop yield in areas with limited water resources. Deficit irrigation can stabilize irrigation performance at a certain level, which leads to a stable income for farmers.
- Due to lower humidity, the risk of plant diseases compared to what is seen in full irrigation is reduced.
- Reduced loss of nutrients due to reduced leaching results in better groundwater quality and less need for fertilized land compared to what is seen with full irrigation.

In contrast to these advantages, deficit irrigation needs the following:

- Detailed information of plant response to water stress.
- Farmer should have free and full access to water at critical stages of deficit irrigation.
- A minimum amount of irrigation water should always be available, which may not be present in very dry areas that have severe water limitation.

Furthermore, the community of all water users should be considered by farmers on a larger scale when facing crop yield loss compared to full irrigation at a small scale.

16.13 Economic Analysis of Deficit Irrigation and Determining Optimum Depth of Irrigation in Sunflower (Case Study: Mazandaran Province, Iran)

The aim of this study is to find optimum irrigation depth for sunflower. This is necessary to determine production and cost functions for applied water. Then, economic parameters can be calculated. The production function selected in this study is a simplified form of nonlinear quadratic polynomial production function, in which only the effect of water quantity on sunflower production area is evaluated with constant consideration of other production factors. An attempt was made to provide the necessary data at a research farm in Sari (53.4E, 39.36N), Mazandaran Province, Iran, in 2012. This trial was carried out with four water treatments including: one full irrigation treatment, two deficit irrigation treatments between 55% and 75% of water requirement, and one irrigation treatment at about 125% of water requirement. It should be noted that the experiment was performed on a 700-sq m piece of land containing clay loam soil, and a drip irrigation system was executed in seven rows with a plant spacing of 20 cm within the rows and a row spacing of 75 cm [19].

The full irrigation requirement of sunflower is calculated using the following equation and is made depending on the irrigation treatment:

$$D_n = \sum_{i=1}^{m} \left[\left(\theta_{FCi} - \theta_{1i} \right) \cdot Bd_i \cdot D_i \right], \tag{16.15}$$

where

θ_{FCi} is the moisture content at field capacity
θ_{1i} is the soil moisture before irrigation
D_i is the depth of root penetration (cm)
Bd_i is the soil density (gr/cm^3)

The daily soil moisture content at different depths was measured using a TDR instrument. The seed production function as a function of the irrigation depth was calculated based on data obtained from field studies using the method of least squares in the form of a quadratic polynomial model. The cost function

TABLE 16.4 Results of Field Trials for Different Treatments

Yield (kg/ha)	Treatment (%)
5335	125
5313	100
4142	75
2931	50

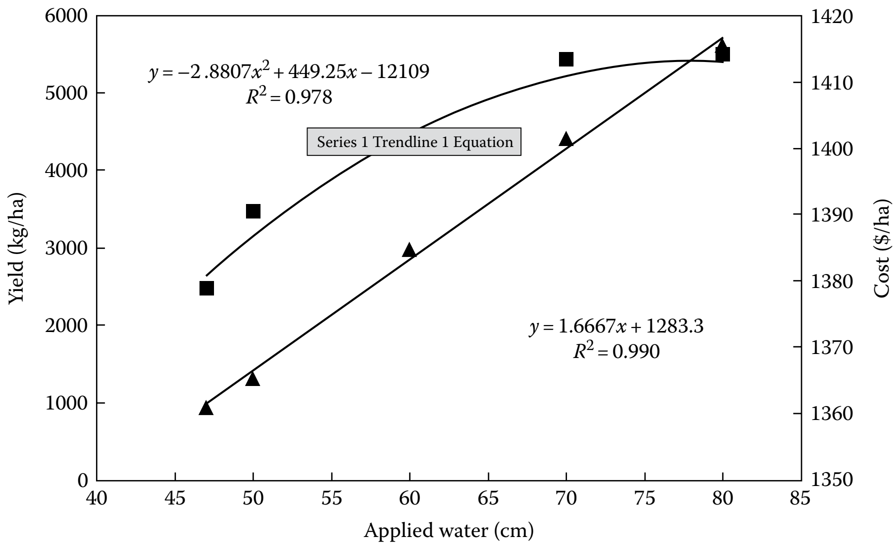

FIGURE 16.5 The production and cost functions of sunflower.

TABLE 16.5 Economic Analysis of Deficit Irrigation Allocation on Sunflower

	Applied Water (cm)	Yields (kg ha⁻¹)	Income ($ ha⁻¹)	Benefit–Cost Ratio (B/C)	Deficit (%)
w_{ew}	67.7	5098	1396	1.52	13
w_w	72.6	5324	2218	1.86*	7
w_{el}	76.6	5401	2250	1.60	2
w_l	77.3	5405	2252	1.60	0.8
w_m	78	5407	2253	1.59	—

* The maximum benefit-cost ratio (1.86) has occurred in 7% deficit.

was obtained based on the total costs of tillage, planting and harvesting assuming a linear relationship between the costs and the amount of applied water in the form of a linear model for the irrigation water depth. Table 16.4 shows the results of field trials from different treatments, and production and cost functions are also presented in Figure 16.5.

As shown in Table 16.4, the highest yield of 5335 kg belongs to the maximum irrigation treatment of 125%, while the lowest yield of 2931 kg is related to the treatment of 55%. Characteristics of irrigation and yield and the benefit–cost ratio are presented in Table 16.5. Table 16.5 shows a rising trend of gross income with increasing applied water depth to the maximum depth (w_m = 78 cm). In other words, the yield and gross income obtained from the yield increase was raised with an increase in irrigation water. The highest yield and gross income correspond to a depth of 78 cm, while the lowest values are related to a depth of 67.7 cm. But since gross income is not the only good indicator of economic optimum, benefit–cost ratio is provided. The maximum indicator compared to the benefit–cost ratio is achieved in the irrigation depth of 72.6 cm. In other words, it can be achieved to the highest benefit–cost ratio with deficit irrigation (7%). Variation in the benefit–cost ratio at different depths indicates that this indicator initially increased with increasing irrigation water depth and reached its maximum level at 7% deficit irrigation, but dropped again to 1.59 under the maximum irrigation.

16.14 Summary and Conclusions

Currently, the agricultural sector is known to be the Earth's largest consumer of water resources. Under the present circumstances, despite limited water resources, competition for water to be used in the agriculture (for irrigation) and domestic, industrial, and environmental sectors imposes limits on water allocations in agriculture. Irrigation techniques can be an effective way to reduce water consumption. Specifically, deficit irrigation techniques can reduce water used for irrigation; a proper irrigation regime in areas where irrigation is impossible can optimize water productivity and provide economic benefits. In fact, deficit irrigation is known as an optimization strategy that results in maximizing economic efficiency due to consciously reducing irrigation followed by yield loss.

Many studies have shown the positive effects of deficit irrigation, which can be observed when agronomic and economic aspects of deficit irrigation are reviewed. In deficit irrigation analysis, observation of the relationship between the depth of irrigation water or evapotranspiration and crop yield is proposed in order to evaluate the sensitivity of plant to water stress during the growing season or at certain growth stages. This relationship varies depending on plant variety, cultivation, irrigation management, irrigation system, and stage of growth at which deficit irrigation is applied. Accuracy in choosing a stage or stages of growth that water stress imposed on the plant is essential for attaining the maximum efficiency and economic benefit. Although the positive effects of deficit irrigation have been proved in many studies, farmer education and familiarity with the scientific and economic aspects of deficit irrigation is necessary so that they may be convinced to apply this technique on their farms.

Authors

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17

Deficit Irrigation: Greenhouse

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Abstract The great challenge for the coming decades will therefore be the task of increasing food production with less water, particularly in countries with limited water and land resources. In areas with dry and hot climates, greenhouse cultivation has improved water-use efficiency (WUE) mainly by reducing runoff and evapotranspiration (ET) losses. The cover utilized on these structures changes locally the radiation balance by entrapping long-wave radiation and creates a barrier to moisture losses. However, complementary approaches are still needed to increase WUE in greenhouse cultivation. This overview presents the results of a number of deficit irrigation (DI) and partial root-zone drying (PRD) studies carried out for various crops under greenhouse conditions, with a review of the impact of reduced water supplies on crop yield. In this chapter, DI concepts are first reviewed and then some management and scheduling in relation to different types of greenhouses are described. Afterward, DI in greenhouse, WUE, crop growth, yield and quality of different ornamental and vegetable crops are investigated. However, high technology greenhouses will facilitate crop management under DI conditions.

17.1 Introduction

Arid and semiarid regions suffer from water scarcity and inadequate renewable water resources. Water scarcity along with a continuous decrease in water resources, coupled with an increasing demand for water in agriculture and in other sectors, has forced farmers to change their irrigation practices and governments to alter their water management strategies. In many parts of the world, both farmers and governmental agencies started changing irrigation strategies by moving from open field to greenhouses and by using irrigation scheduling techniques, such as deficit irrigation (DI) or partial root-zone drying (PRD) irrigation. This could enhance irrigation water savings while maintaining a satisfactory production level [4,5,19].

Greenhouse cultivation is one of the farming systems widely used to provide and maintain a controlled environment suitable for optimum crop production, leading to maximum profits. This includes creating an environment suitable for working efficiency as well as for better crop growth [2]. Depending upon the technical specification of a greenhouse, key factors that may be controlled include temperature, levels of light and shade, irrigation, fertilizer application, and atmospheric humidity. Greenhouses are often used for growing flowers, vegetables, fruits, and transplants. Special greenhouse varieties of certain crops, such as tomatoes, are generally used for commercial production. Many vegetables and flowers can be grown in greenhouses in late winter and early spring and then transplanted outside as the weather warms. The relatively closed environment of a greenhouse has its own unique management requirements, compared with outdoor production. Pests and diseases, and extremes of heat and humidity, have to be controlled, and irrigation is necessary to provide water. Most greenhouses use sprinklers or drip lines. Significant inputs of heat and light may be required, particularly with winter production of warm-weather vegetables. However, greenhouse cultivation is a steadily growing agricultural sector all over the world.

The relationships between crop yield and water use have been a major focus of agricultural research in arid and semiarid regions. As a result, improving crop water-use efficiency (WUE) has been a matter of concern to researchers and agronomists in recent years. WUE is discussed either in terms of instantaneous measurement of the efficiency of carbon gain per water loss by plants or as the integral of such an efficiency over time (expressed as the ratio of biomass accumulation or harvested yield to water use) [10]. The WUE in the agricultural sector has been slowly improving due to the use of genotypes with increased WUE and due to the adoption of innovative cultivation and irrigation practices (e.g., drip irrigation, use of irrigation calendars based on the depth of water table and soil salinity, reuse of wastewater) [17]. DI, mulching, and protected cultivation have contributed to improve WUE in agriculture by significantly reducing runoff and ET losses. Mediterranean countries have led developments in drip irrigation and cultivation under plastic in the past decades, but China has been strongly investing in these techniques. China has recently emerged as the world's largest producer of greenhouse vegetables and ornamentals (close to 2 million ha) and has about 15 million ha using plastic mulches [18]. However, the WUE can be optimized by adoption of more efficient irrigation practices. Therefore, innovations are needed to increase the efficiency of using the available water resources. One approach is to develop new irrigation scheduling techniques, such as DI or PRD, which are not necessarily based on full crop water requirement.

DI is one way of maximizing WUE for higher yields per unit of irrigation water applied. In this method, the crop is exposed to a certain level of water stress either during a particular period or throughout the whole growing season. Many researchers have studied the effects of DI on crop production. PRD is a modified form of DI, which involves irrigating only one part of the root zone in each irrigation event, leaving another part to dry to certain soil water content before rewetting by shifting irrigation to the dry side.

17.2 Terminology

17.2.1 Greenhouse

A greenhouse is a structure with glass walls and roof for the cultivation and exhibition of plants under controlled conditions [7].

17.2.2 Full Irrigation (FI)

Full irrigation (FI) is used by farmers in nonlimited or even water-limited areas. In this method, crops receive full ET requirements, resulting in maximum yield. Nowadays, full irrigation is considered a luxury use of water that can be reduced with minor or no effect on profitable yield [36].

17.2.3 Deficit Irrigation (DI)

Deficit irrigation (DI) is a watering strategy that can be applied by different types of irrigation application methods. The correct application of DI requires thorough understanding of the yield response to water (crop sensitivity to drought stress) and of the economic impact of reductions in harvest [21,22]. In regions where water resources are restrictive, it can be more profitable for a farmer to maximize crop water productivity instead of maximizing the harvest per unit of land [25]. The saved water can be used for other purposes or to irrigate extra units of land [37].

17.2.4 Regulated Deficit Irrigation (RDI)

Regulated deficit irrigation (RDI) is one way of maximizing water-use efficiency for higher yields per unit of irrigation water applied: The crop is exposed to a certain level of water stress either during a particular period or throughout the growing season. The expectation is that any yield reduction will be insignificant compared with the benefits gained through diverting the saved water to irrigate other crops. RDI as an irrigation scheduling technique was originally developed for pome and stone fruit orchards [26]. The reviewed literature evidenced some relevant factors (both positive and negative) affecting the choice to use RDI:

- RDI admits furrow irrigation.
- Control of fruit size and quality can be achieved.
- Vegetative growth can be controlled.
- RDI causes potential yield losses.
- The positive effects of RDI mainly recorded on grape and wine quality.
- Marginal water savings.
- Soil water monitoring is recommended.

17.2.5 Partial Root-Zone Drying (PRD)

Partial root-zone drying (PRD) is a modified form of DI [21,22] that involves irrigating only one part of the root zone in each irrigation event, leaving another part to dry to certain soil water content before rewetting by shifting irrigation to the dry side; therefore, PRD is a novel irrigation strategy since half of the roots is placed in drying soil and the other half grows in irrigated soil [1]. To conclude, the main factors that may affect the choice of PRD are the following:

Drip irrigation is preferred within PRD; alternate row furrow irrigation is possible.

- No effects on fruit size.
- Vegetative growth can be controlled.
- Positive effects on irrigated crop quality.
- Significant water savings.
- Significant effect on cost increase for doubling laterals in cases where it is not necessary technical reasons.
- Soil water monitoring is recommended.

17.2.6 Water-Use Efficiency (WUE)

Water-use efficiency (WUE) is the ratio of net CO_2 assimilation to water used [10]. CO_2 assimilation may be in terms of net CO_2 exchange, dry matter growth, and economic yield, while water used may be determined by mass or molar unit [10]. According to Qiu et al. [45], WUE could be defined as short-term gas exchange on a photosynthesis basis (WUE_{photo}), a biomass basis (WUE_{bio}), or a yield basis (WUE_{grain}). WUE_{bio} could be used to describe the behavior of a plant population in the long term [45].

17.2.7 Crop Yield Response Factor (Ky)

Crop yield response factor (Ky) indicates a linear relationship between the decrease in relative water consumption and the decrease in relative yield. It shows the response of yield with respect to the decrease in water consumption. In other words, it explains the decrease in yield caused by the per unit decrease in water consumption [20].

17.2.8 Irrigation Water-Use Efficiency (IWUE)

Irrigation water-use efficiency (IWUE) is a term used to promote the efficient use of irrigation water at the crop production level. IWUE was estimated by the following equation:

$$\text{IWUE}\left(\text{kg m}^{-3}\right) = \frac{\text{YLD} - \text{YLD}_{\text{rainfed}}}{\text{IRGA}} \tag{17.1}$$

where
YLD is the yield
$\text{YLD}_{\text{rainfed}}$ is the yield obtained from the rain-fed treatment or dryland yield
IRGA is the seasonal irrigation amount used in millimeter

17.3 Types of Greenhouse

Greenhouse types depend greatly on the structure, construction method and material, facilities and equipment used. In central and northern Europe, most greenhouses are glass covered, whereas elsewhere in warmer climates the majority of the greenhouses are covered with plastic film [41]. Globally, the plastic film greenhouses are more than glass greenhouses that have been readily adopted on all five continents, especially in the Mediterranean region, China, and Japan [33].

The common greenhouse types are venlo-type, wide-span, plastic, and arched greenhouse. The shape of the greenhouse structure influences the internal climate of the greenhouse environment especially on temperature, humidity, and light transmission. The shapes that appear most frequently are gable roof or pitched roof, sawtooth or shed roof, round-arched tunnel, round arch with vertical side wall, pointed arch with sloping side wall, and pointed arch with vertical side wall.

The facilities and equipment used inside a greenhouse can classify the greenhouse as a controlled environment greenhouse or not. The equipment includes heating equipment, ventilation and cooling, screens, carbon dioxide (CO_2) enrichment, and supplementary lighting. Greenhouses are a technology-based investment. The higher the level of technology used, the greater is the potential for achieving controlled growing conditions. To find the best estimation of water requirement of crops in a greenhouse, three categories of greenhouse types are examined here according to their technology.

17.3.1 Low Technology Greenhouses

Greenhouses under this category use simple and low technology structure. These greenhouses may be less than 3 m in total height especially for tunnel or igloo type of greenhouse. The tunnel greenhouses generally consist of bent trusses (hoops) which are screwed to the ground by means of screw anchors or cast in concrete [11]. The frame structure is made from wood, bamboo sticks, or steel. They do not have vertical walls and have poor ventilation—mainly passive ventilation. This type of structure is relatively inexpensive and easy to build. Automation equipment is rarely used in this type of greenhouse.

According to Togani and Pardossi [49], the internal climate of the low technology greenhouse is strongly dependent on external conditions. Plastic greenhouses with low technology structures are likely to be susceptible to damage, mainly caused by wind. Moreover, the crop production is limited by the growing environment, which restricts yields and does little to reduce the incidence of pests and diseases.

17.3.2 Medium Technology Greenhouses

Medium technology greenhouses are better in structure as compared to the low technology greenhouses where the supporting structure is galvanized iron and aluminum [49]. They are typically characterized by vertical walls more than 2 m but less than 4 m tall and a total height usually less than 5.5 m. Medium level greenhouses are usually clad with either single or double skin plastic film or glass and use varying degrees of automation. This type of greenhouse is closer to the low technology greenhouse in terms of internal technology, but closer to the high technology greenhouse in terms of internal climate control [49]. This may be due to the use of facilities and equipment for better growth environment. Production in medium level greenhouses can be more efficient than field production.

17.3.3 High Technology Greenhouses

The most sophisticated structures belong to this category. They contain galvanized iron support structures, aluminum glass supports, and almost always use glass as a covering material [49]. The wall construction height is at least 4 m, with the roof peak being up to 8 m above ground level. These high technology structures can provide optimum growth environment through climate control. Air movement (ventilation), temperature, and incident light in the greenhouse can be controlled by various facilities and equipment. The equipment are normally controlled and regulated by an information system. Due to the sophisticated structures and facilities, the greenhouse cultivation is only profitable under high productivity. They are normally limited to industrial areas where production is high. However, with the use of high-level technology greenhouses, the dependency on labor work can be reduced, thus reducing the cost for production.

17.4 Evapotranspiration Models in Greenhouse

Accurate estimation of the ET rate in greenhouses is a key parameter in the water management for greenhouse cultivation. Indirect measurement of ET in greenhouses is a method of calculating ET using microclimate data. Despite the abundance of transpiration models available in the literature [27,30,34], it was found more reasonable to study the ET models as they account for both evaporation and transpiration processes in a greenhouse environment. Moreover, distinguishing both the processes is difficult as they occur simultaneously [3]. The models used in the greenhouses are based on Fazilah Fazlil Ilahi's [24] research on "Evapotranspiration Models in Greenhouses." It is suggested to base the evaporation model on the greenhouse technology and the available information. Through the evapotranspiration models given in "Evapotranspiration Models in Greenhouses," the reference ET can be calculated. The reference ET should be multiplied with a crop coefficient based on the type of crop. Due to the limited data on crop coefficients for very specific crops, only a few of the models mentioned in Ilahi's research [24] could be used. The crop coefficients for most of the crops are given in "Crop coefficient of 40 varieties" (Irrigation Water Management Research Group). Because of the limited data on crop coefficients Ilahi's research [24] is used as a guideline, but the actual models will be limited to the FAO Penman model, the FAO Penman–Monteith Model, the FAO Radiation model, the Hargreaves model, and the Stanghellini model.

Based on Ilahi's research [24], the ET models used in low technology greenhouses were mainly FAO Penman, FAO Penman–Monteith, FAO Radiation, and Hargreaves. These models were developed principally for outdoor conditions. It can be said that the environment inside the low technology greenhouse reflects the outdoor conditions. This is because the internal climate is strongly dependent on external conditions. The structure of the greenhouse itself allows the influence of outdoor climate on internal climate as exchange of air occurs continuously through open doors, windows, and screen-house material. Furthermore, the greenhouse does not have controlled climate equipment that modifies the internal climate.

The ET models used in high technology greenhouse were mainly Stanghellini and Fynn models. These models were mainly developed for greenhouse conditions where air velocities are typically low and have microclimates that differ from outside climate (controlled climate greenhouse) [7]. The application of these models was proven to be reliable for ET calculation in high technology greenhouses. In medium technology greenhouse, however, models developed for both field and greenhouse conditions were applied. In this type of greenhouse, the Stanghellini model gave the most accurate ET estimation, while the original equation of the Priestley Taylor model gave the least accurate estimation. This shows that medium technology greenhouses have a microclimate that represents both conditions in low and high technology greenhouses, especially when the greenhouse uses natural ventilation from opening roofs and windows. On the other hand, ventilation can be controlled by various facilities and equipment in high technology greenhouse.

17.5 Deficit Irrigation Management

The DI practices differ from traditional water supplying practices. The manager needs to know the level of transpiration deficiency allowable without significant reduction in crop yields. The main objective of DI is to increase the WUE of a crop by eliminating irrigations that have the little impact on yield. The resulting yield reduction may be small compared with the benefits gained through diverting the saved water to irrigate the other crops for which water would normally be insufficient under traditional irrigation practices. Before implementing a DI program, it is necessary to know crop yield responses to water stress, either during defined growth stages or throughout the whole season [12,13,38]. High-yielding varieties are more sensitive to water stress than low-yielding varieties. Crops or crop varieties that are most suitable for DI are those with a short growing season and that are tolerant of drought [48]. In order to ensure a successful DI, it is necessary to consider the water retention capacity of the soil. In sandy soils, plants may undergo water stress rapidly under DI, whereas plants in deep soils of fine texture may have ample time to adjust to low soil water matric pressure and may remain unaffected by low soil water content. Therefore, success with DI is more probable in finely textured soils. The following paragraph outlines the analytical capabilities needed for optimum irrigation management and summarizes the general features of an integrated set of analytical tools—a decision support system (DSS)—designed for analysis, evaluation, and implementation of optimum irrigation strategies. The desired capabilities of DSS to facilitate effective management of DI include the following [31]:

- *Modeling application efficiencies*: In conventional practice, application efficiencies are normally assumed *a priori*. However, because application efficiency varies with irrigation intensity, the ultimate disposition of applied water must be explicitly analyzed when water use is less than full irrigation.
- *Modeling crop yields*: Development of science-based models of this relationship is a particular challenge, since they must achieve the model accuracy using input parameters that can be readily determined on a field scale.
- *Conjunctive irrigation scheduling*: Optimal allocation of limited water among multiple fields requires simultaneous scheduling of irrigations for all fields that share a common source of water, rather than scheduling each field independently.
- *Long-range* (*full season*) *forecasting of crop water requirements*: Longer-range forecasting of irrigation requirements enables the managers to better anticipate when irrigation demands will exceed delivery system capacities, providing more time and flexibility to modify irrigation schedules.
- *Comprehensive economic analysis*: The analysis must estimate resource use (energy, water, labor, capital investment) to determine the costs of an irrigation strategy. When water supplies are limited, the analyst must also consider the value of water used for alternative purposes.
- *Feedback*: Field data collected during the season can be used to update and adjust expected irrigation requirements and for iterative recalibration throughout the growing season to develop a more precise and robust analytical engine.

17.6 Deficit Irrigation Scheduling

Understanding of when and how to apply RDI has improved substantially over the past 20 years. Scheduling has evolved from the initial recommendations based on U.S. Class A pan evaporation (E_{pan}) toward measuring both soil moisture and crop responses before making management decisions. Although the original, simple recommendations may still work for many orchards, the emphasis on measuring soil moisture to estimate orchard water use and tree water stress allows more precise control over vegetative vigor and fruit growth. Under trickle irrigation, the original recommendation for scheduling RDI was to irrigate daily and calculate irrigation amount from a percent replacement of E_{pan}. The following is a list of necessary steps to implement RDI successfully:

- Measure fruit and shoot growth to determine the RDI period for fruit species/varieties in an orchard
- Dig up a tree to determine the root-zone distribution—width and depth (80% of total)
- Determine the wetting pattern of the irrigation system and estimate wetted root zone
- Develop a season irrigation plan for run time and interval based on soil type and average E_{pan} or reference crop evapotranspiration (ET_o)
- Install soil moisture sensors (preferred measure is soil suction using gypsum blocks)
  - At 0.3 m and bottom of root zone in shallow soil
  - At 0.3 m, 0.6 m, and bottom of root zone in deep soil

During the RDI period:

1. Measure and record soil suction and irrigate when the entire root zone dries out to a minimum of 200 kPa
2. Irrigate to wet the top 0.3 m of the root zone
3. Measure and record soil moisture 6–12 h after irrigation and, where necessary, adjust the amount applied in previous irrigations
4. Irrigate when the wetted root-zone soil at 0.3 m depth dries out to 200 kPa
5. Measure evaporation (ET_o) interval between irrigations—to irrigate in future years based on this evaporation interval
6. Repeat steps 3–6

17.7 Deficit Irrigation in Greenhouse: Water-Use Efficiency, Crop Growth, Yield, and Quality

The major horticultural production areas are located in hot and dry climates where high light, high temperatures, and high vapor pressure deficit of the air (VPD) often co-occur with low soil water content. DI strategies may help to save more water and optimize or stabilize yields and quality in these areas and they have been investigated for several horticultural crops, namely, grapevines, orchard fruit trees, and vegetables [25,36]. The advantages of DI practices for production of leaf vegetables are less clear than for fruit crops [35]. However, DI practices can be increasingly justified in order to save water, improve nitrate use efficiency, minimize leaching of nutrients and biocide, or in view of higher water prices.

17.7.1 Ornamentals

Cameron et al. [15,16] found that DI (>50% ETc) has commercial potential to reduce excessive growth of several woody ornamentals belonging to the genus Cotinus and Forsythia and to reduce water consumption by 50%–90% relatively to the irrigation used commercially. Moderate water deficits imposed by RDI (at 50% of the ETc) improved commercial crop quality. Shorter internodes and shoots and identical number of primary shoots gave more compact plants and suppressed the need for mid-season pruning [16]. More severe water deficits (at ≤25% of the ETc) resulted in leaf injury and consequently lower quality [16].

Different DI regimes were tested on seedlings of several ornamental species such as *Silene vulgaris* L., *Rosmarinus officinales* L., and *Nerium oleander* L. [8,14,46]. Moderate stress during the nursery phase reduced shoot length, stem diameter, and leaf area by the time of transplantation and roots were shorter, thicker, and less ramified [46]. These morphological changes together with a more efficient stomatal regulation resulted in higher survival rates and better adaptation to transplantation under dry environments due to improvements in the water relations of crop [46].

17.7.2 Vegetables

17.7.2.1 Broccoli

The effect of DI on yield for broccoli grown under unheated greenhouse condition was investigated. Water was applied to broccoli at 1.00%, 0.75%, 0.50%, 0.25%, and 0.00% (as control) of evaporation from a Class A pan corresponding to 2-day irrigation frequency. Irrigation water applied ranged from 70 to 522 mm, and water consumption ranged from 88 to 542 mm. The effect of irrigation water level on the yield, head height, head diameter, head weight, and dry matter was found to be significant. The highest yield and Ky factor found were 29.2 ton/ha and 1.04, respectively. The highest values for WUE and IWUE were found to be 6.71 and 6.50 kg/m^3 for the 0.75 of evaporation from a Class A pan treatment [9].

17.7.2.2 Pepper

Guang-Cheng et al. [29] used the greenhouse-grown hot pepper to investigate the effect of Time-Space deficit irrigation (TSDI), a newly developing irrigation technique based on RDI and PRD, by measuring plant growth, yield, and irrigation water-use efficiency. The experiment was conducted during warm-wet season in a glass greenhouse in southern China [28].

Three irrigation strategies (conventional furrow irrigation with full water when soil water content was lower by 80% of field capacity [F], conventional furrow irrigation with 50% of full water [D], and alternate furrow irrigation with 50% of full water [P]) as the main plot factor were applied to select the optimum irrigation parameter at different stages of crop development; the treatment in which irrigation water was applied to both sides of root system when soil water content was lower by 80% of field capacity during all stages was considered as control (FFFF). Water consumption showed some significant effect of irrigation treatment during the growing period of different drought stress patterns application and therefore decreased in these treatments to a level around 54.68%–70.33% of FFFF. Total dry mass was reduced by 1.17%–38.66% in TSDI treatments compared to FFFF. However, the root–shoot ratio of FFFF was lower than other treatments and the differences from FFFF and other TSDI treatments were statistically significant. The highest total fresh fruit yield (19.57 ton/ha) was obtained in the FFFF treatment. All DIs increased the water-use efficiency of hot pepper from a minimum of 1.33% to a maximum of 54.49%. At harvest, although there was a difference recorded as single fruit weight and single fruit volume was reduced under the TSDI treatments, total soluble solids concentration of fruit harvested under the water-deficit treatments were higher compared to FFFF.

17.7.2.3 Tomato

Kirda et al. [39] used greenhouse-grown tomato to test PRD and DI in spring- and fall-planted fresh-market tomato cultivar. Six irrigation treatments were tested during the 2-year work: (1) FULL, control treatment where the full amount of irrigation water, which was measured using Class-A pan evaporation data, was applied to the roots on all sides of the plant; (2) 1PRD30, 30% DI with PRD, in which wetted and dry sides of the root zone were interchanged with every irrigation; (3) 1PRD50; (4) 2PRD50, 50% DI with PRD, in which wetted and dry sides of the root zone were interchanged every and every other irrigation, respectively; (5) DI30; and (6) DI50, 30% and 50% deficit irrigations, respectively. The defined deficit levels were all in comparison to full irrigation (FULL). During the first year study in 2000, only three treatments (FULL, 1PRD30, and 2PRD50) were tested. Five treatments with the exception of 2PRD50 were included in 2001. The FULL treatment, in spring-planted tomato having a 153-day growth period, yielded 110.9 ton/ha. The resulting IWUE was 321.8 kg/(ha mm). The 1PRD50 treatment gave 86.6 ton/ha, which was not statistically different ($P \leq 0.05$) from FULL (the control) and had 56% higher IWUE. Although yield differences were not statistically significant in fall-planted tomato, the highest fruit yield was again obtained under FULL treatment (205.2 ton/ha) over a growth period of 259 days after transplanting. The PRD treatments had 7%–10% additional yield over the DI receiving the same amount of water. The PRD treatments gave 10%–27% higher marketable tomato yield (>60 g per fruit), compared with the DI treatments. Meidanshahi et al. [44] studied yield, yield components, and WUE of tomato, using PRD irrigation method and a growth stabilizer in two soil textures, under greenhouse conditions in Isfahan, Iran. The factorial experiment, based on complete randomizal design and three replications, included three irrigation managements (T1, FULL; T2, 50% of full irrigation [50%FULL], with PRD method and barrier; T3, 50%FULL, with PRD method and no barrier), two levels of stabilizer (B1, spraying sodium salicylate, and B2, without spraying sodium salicylate) and two soil textures (S1, clay loam, and S2, sandy loam). The results showed that the highest plants (176.2 cm) were in T1 treatment and the shortest plants (131.3 cm) were in T3 treatment. With 50% reduction of water in T2 compared to T1 treatment, the number of flower stems was decreased by 15.2%. The highest and the least biomass and fruit yield were measured in T1 (506.8 and 342.5 g per plant) and T3 (126.2 and 54.8 g per plant) treatments, respectively. WUE was increased by 9.9% (changing from T1 to T2) and was decreased by 71.4% (changing from T2 to T3). The highest and the least fruit yield (216.7 and 174.4 g per plant) were obtained in S2 and S1 soils, respectively. Sandy loam soil with production of 7.22 kg/m^3 had higher WUE than clay loam soil, which produced 5.38 kg/m^3. Application of stabilizer increased fruit yield by 16% and WUE by 16.86%. In general, the effect of PRD irrigation method (with barrier) and spraying sodium salicylate on reducing water use and increasing productivity in greenhouse production of tomato was positive and recommendable.

17.7.2.4 Cucumber

Mao et al. [43] examined DI on greenhouse-grown cucumber in China. The level of fulfillment of water requirements was used as a gauge to differentiate five border irrigation treatments. Fresh fruit yields were highly influenced by the total volume of irrigation water at every growth stage. The treatment with minimum irrigation water applied had the lowest productions. The mathematical functions that better fit the production obtained with the water volume received were linearism, but the functions of evapotranspiration and yield were second-degree polynomials. The WUE and IWUE decreased with the increase in irrigation water applied from stem fruiting to the end, significantly since harvesting of zenith fruits. But WUE and IWUE were ascending with the increase in irrigation water from cucumber field setting to first fruit ripening. Well irrigation along the whole cycle was a clearly advisable irrigation regime. On the other hand, the least advisable regimes were those that lead to deficiencies from harvest of the first fruit to the zenith fruits. But they strongly recommended that actions be taken to limit the inefficient soil evaporation that resulted from higher temperature at the last growth stages in order to improve WUE and IWUE. Alomran et al. [6] investigated a DI system for its impact on soil salinity, Ky, CWP, and yield of greenhouse-grown cucumber. Cucumber seeds were planted in the greenhouse equipped with drip irrigation system. The crop evapotranspiration (ETc) was assessed through pan evaporation method (PE) and estimation based upon Penman–Monteith equation (PM). The results revealed a good agreement between PE and PM ETc. The irrigation treatments consisted of four levels of ETc (40%, 60%, 80%, and 100% of ETc) in addition to the traditional one as practiced by local farmers. At the 60% and 80% ETc treatments, the DI was tested at different growth stages (initial, developmental, middle, and late stages of crop growth). Each of the treatments was carried out in three replicates. The results showed that soil salinity in general increased with decreasing level of applied water. The crop cucumber could tolerate shortage of water during the middle season growth stage, when the Ky values ranged between 0.57 and 0.76. The level of water used in 100% ETc treatment was much lower than that in the traditional drip irrigation as practiced by farmers. In other words, the CWP values increased with water consumption being decreased. The results also indicated that the highest values for CWP were found for the most stressed treatment of 40% ETc, while on the other hand, the overall crop productivity had been decreased [40].

17.7.2.5 Potato

According to Shock and Feibert [47], the economic opportunities for using DI in potato (*Solanum tuberosum* L.) are more limited than for other crops because potatoes have a shallow root system and are very sensitive to water stress. Research has shown that those yield and tuber grades are considerably reduced by soil water deficits even when briefly applied [47]. The negative effect depends not only on the cultivar but also on the phonological phase [32]. Severe reductions in tuber yield and quality occurred when brief periods of water stress were imposed following tuber set. Fabeiro et al. [23] showed for the cultivar "Agria" that applying moderate water deficit during growth and tuber bulking resulted in similar yields to fully irrigated plants and that the smallest yields were obtained when deficit was applied in the last part of the growth cycle. Liu et al. [42] showed no advantage in using PRD (at 50% ETc) relatively to the conventional DI regarding biomass accumulation and WUE when it was applied at the tuber initiation stage.

17.8 Summary and Conclusions

Water scarcity is a fact of life in arid and semiarid regions where agricultural, domestic, and industrial demands compete for limited water resources. Continuous population growth, rising standards of living, industrialization, urbanization, and climate changes have increased water demand significantly. Various countries in arid and semiarid regions are facing water shortage issues due to low precipitation and high evaporation. This complicates the supply of water for domestic, industrial, and agricultural uses. A long-term perspective in shortage of freshwater resources, especially in arid and semiarid areas, highlights an urgent need for innovative irrigation strategy and agricultural water management. At the same time, the need to meet the growing demand for food will require increased crop production from less water. Achieving greater efficiency of water use will be a primary challenge in the near future and will include the employment of techniques and practices that deliver a more accurate supply of water to crops. In this context, DI can play an important role in increasing WUE. Published reports show that DI strategies can be successfully applied to several important vegetable and ornamental crops in the greenhouse, in particular to those that are typically resistant to water stress, in order to improve WUE and save water. However, contrasting results described for the same species suggest that a better understanding is needed on how the cultivar, rootstocks, or soil characteristics influence the plant responses to water deficit. Better knowledge on the vulnerability of each developmental phase of plants to water deficits is also necessary in order to set the most adequate RDI, DI, or PRD irrigation scheduling. Combination of DI strategies with other practices like mulching or protected cultivation may also help to improve WUE and minimize losses in yield or quality in vegetable crops. It is imperative to investigate the sustainability of DI via long-term experiments and modeling efforts to determine to what extent it can contribute to the permanent reduction of irrigation water use. Finally, developments in monitoring systems to precisely assess plant water status in greenhouse conditions will facilitate crop management under DI conditions.

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18

Deficit Irrigation: Optimization Models

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Abstract Water scarcity is a worldwide problem and the best solution is to make an efficient use of water in the agricultural sector. The use of deficit irrigation is a suitable method in water scarcity conditions. In this chapter, two optimization models are explained for surface deficit irrigation to maximize the net income and application efficiency and minimize the total costs. Therefore, it developed the production function of the crops and a model for simulation of advance phase in surface irrigation. The output of these models gives us the design variables of surface irrigation. Two case studies will be presented to show the result of application of the models for a given region of Iran. These studies validate the fact that deficit irrigation is an efficient method in water scarcity conditions.

18.1 Introduction

According to EU2007 [13], water scarcity is defined as a situation where insufficient water reservoirs are available to satisfy the long-term average requirements. Population growth and improvement in living standards have increased water demand worldwide along with decreasing water supply as a result of climate change and the vulnerability to drought events [7]. Under the influence of climate, geology, soils, land use, and hydrological responses, drought exhibits a considerable temporal and spatial diversity that must be taken into account when designing and managing public water supply systems [30].

Water shortage is a worldwide problem and the best solution is to make an efficient use of water in agriculture. When irrigation water is insufficient, the maximum attainable income for an irrigated field may be achieved by deficit irrigation. These days, many farmers are deliberately under-irrigating some fields to increase the net income, often with little guidance from the research community [12]. In deficit irrigation, two distinct decisions to be made are how much water and how much land should be allocated to each crop to maximize the net income that is made by the optimization models. These models have been used extensively in water resources systems analysis and planning [18]. The problem of irrigation scheduling in case of limited seasonal water supply has been studied extensively for single-crop situation [6,22]. A number of researchers have investigated the problem of allocation of limited water supply for irrigation in a multicrop environment [16,20,23,24,29,32,33,34]. Prasad et al. [21] developed a multilevel optimization model by dynamic programing that can be used as a planning tool for allocating the annual available limited water and land at various levels, which maximizes the annual net income. The results reveal that the optimization approach can significantly improve the annual net income with deficit irrigation strategy under water scarcity. Ali et al. [2] investigated deficit irrigation on yield, water productivity, and economic return of wheat in Bangladesh. The grain and straw yield were significantly affected by treatments. The highest water productivity and productivity of irrigation water were obtained in the alternate deficit irrigation, where deficits were imposed at maximum tillering (joining to shooting) and flowering to soft dough stages of growth period. Under both land and water limiting conditions, the alternate deficit irrigation showed the maximum net financial return. Samiha et al. [27] used a yield-stress model for wheat under the application of full irrigation amounts and under deducting 20%–30% full irrigation in Egypt. The results indicated that under deducting 30% of full irrigation, wheat yield will be reduced by less than 6%. Thus, it could help in saving up to 24% of the applied irrigation water with almost no wheat yield losses.

18.2 Development of Optimization Models for Deficit Irrigation

Optimal planning of surface irrigation methods is one of the effective methods in water scarcity conditions. Generally, the surface irrigation planning methods or methods for computing the advance time (an important parameter in designing) can be categorized into the following groups:

Group one: Simple methods like the Soil Conservation Service (SCS) method. Reddy and Clyma [26] and Reddy and Apolayo [25] used the SCS equation for optimal planning of the furrows and considered the total irrigation expense as the objective function. However, findings showed that this method led to considerable errors in computing the advanced time [3,35].

Group two: The numerical methods include the kinematic wave, zero inertia, and dynamic wave models. These methods are complex and also cannot compute the advance time explicitly [31]. Strelkoff and Katopodes [31] and Elliott et al. [11] used the zero inertia models for computing the advance time. The water flow of surface irrigation exhibits a major characteristic, which is the existence of wet–dry boundary [1,17]. In numerical simulation, due to the anti-diffusion characteristic of the roughness term of the Saint-Venant equations, wet–dry boundary of the surface flow can impact the stability of momentum conservation equation and reduce the simulation accuracy of iterative coupled models [8,14].

Group three: The volume balance model. In this model, the surface and subsurface shape factors during the advance stage are assumed to be constant. Also, this model is based on the normal depth. Walker and Skogerboe [37] reported that the volume balance model is more appropriate for advanced computation. Users of the volume balance model need to be aware that uncertain surface volume calculations can lead to potentially large volume balance errors. Thus, these results need to be interpreted carefully [4].

None of the these methods seem appropriate in planning the optimal surface irrigation, since these methods cannot compute the advance time explicitly and precisely. The optimum conditions and the alternate furrow fertigation strongly reduce water and nitrate losses compared with the conventional furrow irrigation. The simulation optimization model is a valuable tool for alleviation of the environmental impact of the furrow irrigation [9,10,19].

Gonc et al. [15] reported that adopting water and deficit irrigation were generally difficult in economic terms, and thus, it is necessary to support the farmers.

Optimal design needs a mathematical equation for explicit computation of the advance time and for using it in the objective function. In this chapter, the total required cost for one irrigation including the workforce cost, water, the furrows, and ditch digging has been considered as the objective function that should be minimized. Obviously, the workforce cost is a function of the irrigation time that depends on the advance time. Valiantzas' equation is an explicit equation for the computation of the advance time based on the results of the zero inertia model with high precision [36].

Here, two type models are explained for deficit irrigation conditions.

18.2.1 Model 1

A simple optimization method is developed to apply when water is limited. Programming requirement and computation time of this method are significantly less in comparison with other sophisticated models. To develop a simple method for economic analyzing of deficit irrigation, the crop production, gross, and net income functions must be determined. It is supposed that the crop production functions can be presented by a quadratic polynomial as follows [12]:

$$y_1(w) = e_1 w^2 + f_1 w + g_1 \tag{18.1}$$

$$y_2(w) = e_2 w^2 + f_2 w + g_2 \tag{18.2}$$

where

w is the total depth of applied water (mm)

$y_1(w)$ and $y_2(w)$ are major (grain) and minor (such as straw) yield per unit of land, respectively, as a function of w (kg/ha)

e_1, f_1, g_1, e_2, f_2, and g_2 are the empirical coefficients

The gross income function is determined from crop price multiplied by yield function as follows:

$$I_g\left(w\right)=A\left[\left(p_1e_1+p_2e_2\right)w^2+\left(p_1f_1+p_2f_2\right)w+p_1g_1+p_2g_2\right] \tag{18.3}$$

where
$I_g(w)$ is the gross income from irrigated lands (Rials)
A is the total crop irrigated area (ha)
p_1 and p_2 are the major and minor yield prices, respectively (Rials/kg)

The cost function is shown as follows:

$$C\left(w\right)=A\cdot\left[C_1\left(w\right)+C_2\left(w\right)+C_3\left(w\right)+C_4\left(w\right)+C_5\right] \tag{18.4}$$

where
$C(w)$ is the production costs of irrigated lands (Rials)
$C_1(w)$ is the cost of applied water per unit of land (Rials/ha)
$C_2(w)$ is the costs of labor and energy per unit of land (Rials/ha)
$C_3(w)$ and $C_4(w)$ are the cost of major and minor yield transportation per unit of land (Rials/ha), respectively, which are all a function of w
C_5 is the cost of preparation of land, planting, and harvesting that are not dependent on w

The coefficient of 10 converts the depth to the volume of applied water per hectare, therefore, $C_1(w)$ and $C_2(w)$ are as follows:

$$C_1\left(w\right)=10wc_1 \tag{18.5}$$

$$C_2\left(w\right)=10wc_2 \tag{18.6}$$

where
c_1 is the price of unit volume of irrigation water (Rials/m_3 of water)
c_2 is the costs of labor and energy for unit volume of irrigation water (Rials/m_3 of water).
$C_3(w)$ and $C_4(w)$ are determined based on the yield functions as follows:

$$C_3\left(w\right)=c_3\cdot y_1\left(w\right) \tag{18.7}$$

$$C_4\left(w\right)=c_4\cdot y_2\left(w\right) \tag{18.8}$$

where c_3 and c_4 are the costs of major and minor yield transportation per unit of weight, respectively (Rials/kg).

By combining Equations 18.4 through 18.8, $C(w)$ can be determined as follows:

$$C\left(w\right)=A\left[\left(c_3e_1+c_4e_2\right)w^2+\left(c_3f_1+c_4f_2+10c_1+10c_2\right)w+c_3g_1+c_4g_2+C_5\right]. \tag{18.9}$$

Using Equations 18.9 and 18.3 (the gross income minus the costs), the net income function is determined as follows:

$$I_n\left(w\right)=A[\left(p_1e_1+p_2e_2-c_3e_1-c_4e_2\right)w^2+\left(p_1f_1+p_2f_2-c_3f_1-c_4f_2-10c_1-10c_2\right)w$$
$$+p_1g_1+p_2g_2-c_3g_1-c_4g_2-C_5] \tag{18.10}$$

where $I_n(w)$ is the net income attained from the irrigated lands (Rials).

When water is limited, A is a function of w, thus the farm manager may put enough land under irrigation to make efficient use of the water supply. The total crop irrigated area can be determined as follows:

$$A = \frac{V_t}{10w} \tag{18.11}$$

where V_t is the total available water supply (m^3). A combination of Equations 18.10 and 18.11 gives the following:

$$I_n(w) = 0.1V\left[\begin{array}{l}(p_1e_1 + p_2e_2 - c_3e_1 - c_4e_2)w + (p_1f_1 + p_2f_2 - c_3f_1 - c_4f_2 - 10c_1 - 10c_2) \\ + \dfrac{(p_1g_1 + p_2g_2 - c_3g_1 - c_4g_2 - C_5)}{w}\end{array}\right] \tag{18.12}$$

To determine the depth of applied water that will maximize the net income when water is limited, we should take the partial derivative from Equation 18.12 with respect to w and set the derivative to zero:

$$\frac{dI_n(w)}{dw} = 0 \rightarrow w = \left[\frac{g_1(p_1 - c_3) + g_2(p_2 - c_4) - C_5}{e_1(p_1 - c_3) + e_2(p_2 - c_4)}\right]^{0.5} \tag{18.13}$$

After calculating optimal w (Equation 18.13), the total crop irrigated area can be calculated using Equation 18.11.

18.2.2 Model 2

To develop a model for irrigation of a piece of specified farm land using the furrow irrigation, it must be divided into a number of irrigation sets (N_s). Each irrigation set composes a number of the furrows that are concurrently irrigated. The arrangement of irrigation sets is presented in Figure 18.1.

Here, N_{sl} is the total number of irrigation sets in the direction of the furrows, N_{sw} is the total number of irrigation sets in the direction perpendicular to the furrows, L_f is the length of farm in meters (in the direction of the furrows), W_f is the width of farm in meters (in the direction perpendicular to the furrows), Q_0 is the inflow rate to each of the furrows (m^3/min), Q_t is the total available flow rate (m^3/min), L is the length of each of the furrows (m), and N_{fs} is the number of furrows.

Regarding Figure 18.2, Equations 18.14 through 18.17 include

$$N_{sl} = \frac{L_f}{L} \tag{18.14}$$

$$N_{fs} = \frac{Q_t}{Q_0} \tag{18.15}$$

$$N_{sw} = \frac{W_f}{W \cdot N_{fs}} \tag{18.16}$$

$$N_s = N_{sl} \cdot N_{sw} \tag{18.17}$$

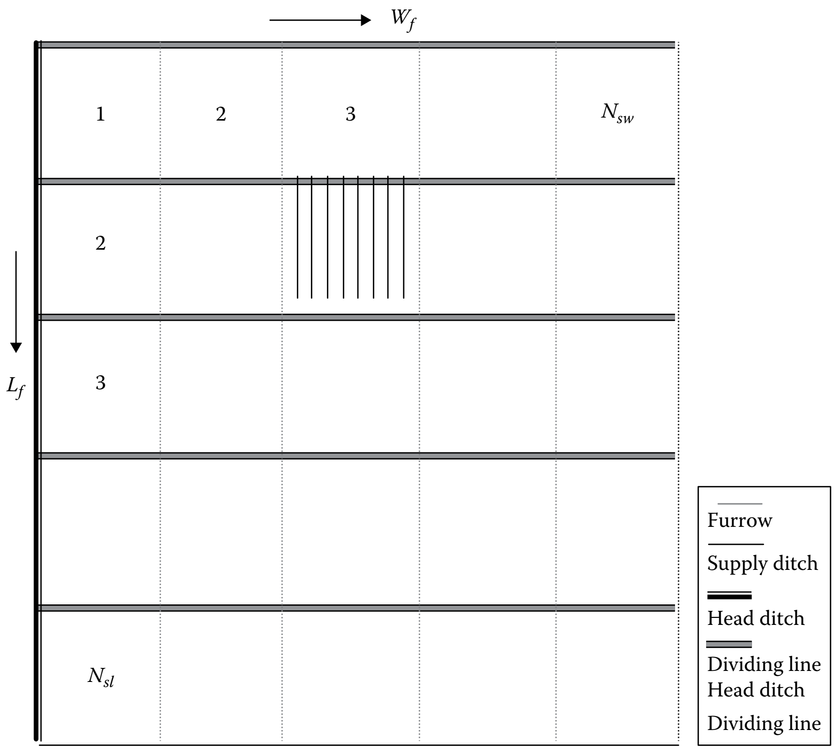

FIGURE 18.1 Furrow irrigation arrangement for model 1.

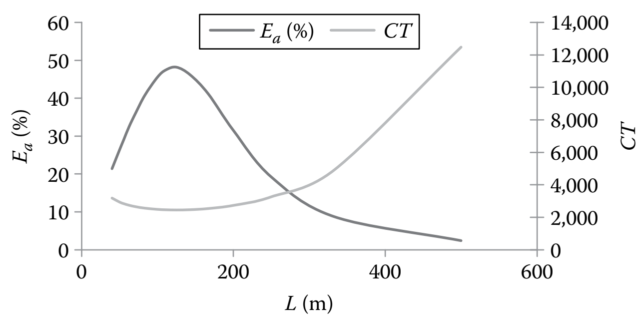

FIGURE 18.2 Sample of cost and irrigation efficiency variations related to length of furrow.

Substituting Equations 18.14 and 18.16 into Equation 18.17, we obtain the following equation:

$$N_s = \frac{W_f \cdot L_f \cdot Q_o}{L \cdot W \cdot Q_t} \tag{18.18}$$

Costs of the furrow irrigation can be divided into four parts that are explained in the following text.

18.2.2.1 Water Cost

Water cost is computed by multiplying the required water volume and the price of unit volume of water (m^3):

$$C_{tw} = Q_t \cdot T_{co} \cdot N_s \cdot C_w \tag{18.19}$$

where

C_{tw} is the cost of the required water for one time irrigation of the whole farm (Rials)
C_w is the price of water volume unit (Rials/m^3)
T_{co} is the cutoff time (min)

By substituting Equation 18.18 into Equation 18.19, the following equation is obtained:

$$C_{tw} = \frac{C_w \cdot W_f \cdot L_f \cdot Q_0 \cdot T_{co}}{W \cdot L} \tag{18.20}$$

18.2.2.2 Workforce Cost

This cost is obtained by multiplying the required time for irrigating the whole farm and the workforce cost in the unit of time as follows:

$$C_{tl} = T_{co} \cdot N_s \cdot C_l \tag{18.21}$$

where

C_{tl} is the workforce required expense for one time irrigation of the entire farm (Rials)
C_1 is the workforce cost for unit of time (Rials/min)

By substituting Equations 18.5 and 18.8, the following equation is obtained:

$$C_{tl} = \frac{C_l \cdot W_f \cdot L_f \cdot Q_0 \cdot T_{co}}{W \cdot L \cdot Q_t} \tag{18.22}$$

18.2.2.3 Furrow Digging Cost

The furrow digging cost is obtained by multiplying the total length of the furrows and the digging cost of their length unit, which concerns the whole growing season. For one time irrigation, it must be divided by the number of irrigation events:

$$C_{tf} = \frac{L_f \cdot W_f \cdot C_f}{N_i \cdot W} \tag{18.23}$$

where

C_{tf} is the cost of the furrow digging for one time irrigation of the whole farm (Rials)
C_f is the cost of digging the furrow length unit (Rials/m)
N_i is the number of irrigation events during the growing season

This cost is not a function of planning variables like the inflow rate and the furrow length. Therefore, its value is constant. It is only involved in computing the total costs and is not important in the calculation of the optimization.

18.2.2.4 Cost of Digging the Head Ditch

According to Figure 18.2, a head ditch dug up at the end of furrows upstream for several irrigation sets. The cost of these ditches computes by multiplying their total length to the digging cost of length unit. Similar to the previous section, this cost should be divided by the number of irrigation events:

$$C_{tf} = \frac{L_f \cdot W_f \cdot C_f}{N_i \cdot W} \tag{18.24}$$

where

C_{td} is the cost of digging the irrigation streams for one time irrigation of the whole farm (Rials)
C_d is the expense of digging the length unit of stream (Rials/m)

By substituting Equations 18.14 and 18.24, the following equation is obtained:

$$C_{td} = \frac{W_f \cdot L_f \cdot C_d}{L \cdot N_i} \tag{18.25}$$

The total cost of irrigation for the growth season is calculated by the following equation ($W_f L_f$ is the irrigated area and according to Equation 18.11 is $V_t/10w$):

$$CT = \frac{Q_o T_{co} V_t N_i}{10WLw}\left(C_w + \frac{C_l}{Q_t}\right) + \frac{V_t}{10w}\left(\frac{C_f}{W} + \frac{C_d}{L}\right) \tag{18.26}$$

where C_t is the total irrigation cost for one time irrigation of the farm (Rials). The benefit function becomes

$$BT = Y(w) \cdot P\frac{V_t}{10w} - \frac{Q_o T_{co} V_t N_i}{10WLw}\left(C_w + \frac{C_l}{Q_t}\right) - \frac{V_t}{10w}\left(\frac{C_f}{W} + \frac{C_d}{L}\right) \tag{18.27}$$

where

$Y(w)$ is the production function
P is the price of the production

Equation 18.27 indicates that the benefit depends on four decision variables including Q_0, T_{co}, w, and L. The benefit equation is as an objective function in optimization model. T_{co} can be written as sum of advance and intake opportunity times:

$$T_{co} = T_l + T_r \tag{18.28}$$

where

T_l is the advance time (min)
T_r is the intake opportunity time (min)

Equation 18.28 is considered as a constraint function in optimization problem.

To compute T_r, any infiltration equation can be used. For the Kostiakov equation, computation is as follows:

$$T_r = \left(\frac{Z_r}{K}\right)^{1/\alpha} \tag{18.29}$$

where

Z_r is the net irrigation requirement (m)

K and α are the infiltration coefficients of the Kostiakov equation

To compute T_l, an explicit and precise equation should be used. For this purpose, the following equation that was proposed by Valiantzas [35] is used:

$$T_l = (1+0.15\alpha)\cdot\frac{L\cdot A_0}{Q_0} + \left(\frac{\sigma_z\cdot K\cdot L}{Q_0}\right)^{1/(1-\alpha)} \tag{18.30}$$

where

A_0 is upstream cross sectional flow area (m^2)

σ_z is the subsurface flow shape factor

This coefficient is computed from the following equation:

$$\sigma_z = \frac{\alpha\cdot\pi\cdot(1-\alpha)}{\sin(\alpha\cdot\pi)} \tag{18.31}$$

A_0 value is computed using the Manning equation and the furrow form coefficients are computed using the following equation:

$$A_0 = \left(\frac{N^2 Q_0^2}{3600 S_0\cdot\rho_1}\right)^{1/\rho_2} \tag{18.32}$$

where

N is the Manning's roughness coefficient

S_0 is the furrow bed slope (m/m)

ρ_1 and ρ_2 are the furrow shape coefficients

All of the mentioned computations are performed using LINGO and finally L, Q_o, T_{co}, w, and the maximum benefits are computed. Then, the application irrigation efficiency (E_a) can be computed:

$$E_a = \frac{Z_r\cdot W\cdot L}{Q_0\cdot T_{co}}\times 100 \tag{18.33}$$

According to Equation 18.27, along with maximization of B_t, the value of $Q_o T_{co}$ will be minimized and thus according to Equation 18.33, irrigation efficiency will be maximized.

18.2.2.5 Example for Model 2

The following data for the furrow optimized planning have been introduced into the optimization:

$$Z_r = 0.1\text{ m},\quad Q_t = 9.48\text{ m}^3/\text{min},\quad K = 0.0016,\quad a = 0.762,\quad W = 0.76\text{ m}$$

$$N_i = 7,\quad n = 0.04,\quad S_0 = 0.001,\quad \rho_1 = 0.3269,\quad \rho_2 = 2.734,$$

$$W_f = 100\text{ m},\quad L_f = 1000\text{ m},\quad C_l = 60\text{ Rials/min},\quad C_f = 100\text{ Rials/m}$$

$$C_d = 200\text{ Rials/m},\quad C_w = 20\text{ Rials/m}^3$$

The results of the optimization model based on minimizing the cost function for one time irrigation are as follows:

$$L = 100\ \text{m},\quad Q_0 = 0.0498\ \text{m}^3/\text{min},\quad T_{co} = 312\ \text{min},\quad E_a = 48.7\%,\quad CT = 2,450,000\ \text{Rials}$$

In this example, the minimum irrigation cost and maximum irrigation efficiency are obtained for the inflow rate of 0.0498 (m^3/min) and length of 100 (m) for the furrow. According to the flow rate, by increasing or decreasing the furrow length, a decrease in the irrigation efficiency and an increase in its cost would be caused, respectively. The slope of cost and irrigation changes relative to the furrow length has the optimal points that were shown in Figure 18.2. Similarly, the slope of cost and irrigation efficiency relative to inflow rate can be drawn for a furrow in the length of 100 m. In this case, by increasing or decreasing the inflow rate, the irrigation cost increases and irrigation efficiency decreases, respectively.

According to the findings of Booher [5], a furrow length of 190 m is obtained, the furrow length is a function of depth of irrigation water, bed slope of the furrow, and soil texture. The other furrow properties have not been considered. According to Figure 18.2, irrigation efficiency is 32% for the furrow length of 190 m.

The following comments are recommended here.

The optimal furrow design curves can be drawn for the variety of soils and the furrows for various values of net irrigation requirements.

The issue of low irrigation can be easily inserted into this method. For this purpose, it is assumed that percolation at the end of the furrow is less than the net irrigation requirement.

18.3 Case Studies

18.3.1 Case Study 1: Application of Model 1

The experiment was conducted on winter wheat at the research farm of Shahrekord University, Chaharmahal-Va-Bakhtiary Province, Iran, as a completely randomized design that consisted of nine irrigation treatments, T1 to T9, with four replications (36 plots 1 × 1 m) in 2006. The soil texture was sandy loam and the water holding capacity was 100 mm/m (10%). The climate was semiarid (according to De Marten method) with an annual rainfall of about 380 mm. The irrigation method was the basin approach. The distance between the plots was 1 m. In each plot, 30 g grain was sowed. T1 and T2 treatments were over-irrigated, and T3 was full irrigated. The other treatments were under the deficit irrigation regime. The depth of applied water in T3 treatment was calculated by a local calibrated FAO–Penman–Monteith equation. The irrigation interval was 7 days. The depths of applied water in the treatments under deficit irrigation were a percentage of the depth of full irrigation and were 90%, 80%, 70%, 60%, 50%, and 40% for T4 to T9, respectively. Treatments of T1 and T2 were over irrigated for 110% and 120% of the full irrigation depth. The volumes of applied irrigation water during growth season were measured by a volumetric counter and they are shown in Table 18.1. After harvesting 0.5 m^2 from the center of each plot (the size of the plots was 1 × 1 m), the weight of grain and straw were measured (Tables 18.1 through 18.3). The prices and production costs that are required for the economic analyzing have been listed in Table 18.4.

TABLE 18.1 Volume of Irrigation Water and the Weight of Grain and Straw in Different Treatments

Treatment	T1	T2	T3	T4	T5	T6	T7	T8	T9
Volume of irrigation water (L)	360	330	300	270	240	210	180	150	120
Weight of grain (kg/ha)	5660	5680	5626	5568	5510	5452	5394	5000	4760
Weight of straw (kg/ha)	6805	6800	6734	6687	6615	6523	6277	5816	5675

TABLE 18.2 The Results of Weight of Grain in Each Plot (gram per 0.5 m^2)

	Treatment								
Replication	T1	T2	T3	T4	T5	T6	T7	T8	T9
1	287	280	275	273	271	273	263	241	241
2	268	285	277	279	266	253	266	269	235
3	287	269	291	280	290	285	269	245	233
4	290	302	282	281	276	280	280	248	245
Average	283	284	281.25	278.25	275.75	272.75	269.5	260.75	238.5

TABLE 18.3 The Results of Weight of Straw in Each Plot (gram per 0.5 m^2)

	Treatment								
Replication	T1	T2	T3	T4	T5	T6	T7	T8	T9
1	345	338	335	329	327	298	316	290.2	281
2	333	340	330	332	331	417	318.9	280	283
3	343	331	339	337.7	340	304	320.5	297	287
4	340	351	342.8	338.3	325	285.6	300	296	284
Average	340.25	340	336.7	334.35	330.75	326.15	313.85	290.8	283.75

TABLE 18.4 Prices and Production Costs

Parameter	Unit	Amount
p_1	Rials/kg	2,500
p_2	Rials/m^3	600
c_1	Rials/m^3	30
c_2	Rials/kg	50
c_3	Rials/kg	100
c_4	Rials/kg	300
c_5	Rials/ha	10,000,000

Tables 18.1 and 18.2 show the maximum grain that yield in treatment T2. Therefore, the depth of full irrigation is 330 mm (330 L) for each irrigation, whereas this depth based on FAO–Penman–Monteith model was 300 mm. This is due to an incorrect estimation of the depth of full irrigation using this model.

According to Table 18.1, the yield functions were drawn in Figures 18.3 and 18.4; thus, $e_1 = -0.023$, $f_1 = 14.526$, $g_1 = 3386$, $e_2 = -0.0279$, $f_2 = 18.145$, and $g_2 = 3857$.

According to Figure 18.4, the depth of irrigation that maximizes the yield is 314 mm. While for the water limiting situation, the optimum depth of the applied water using Equation 18.13 is 106 mm, that is, equal to 34% of full irrigation. This percentage was 50 for winter wheat (crop price was 0.147 Rials/kg) in Columbia Basin by an analytical framework [12]. By increasing the crop price, this percentage will be increased, because according to Equation 18.13 and $e_1 < g_1$, the optimum depth of applied water (w) will be increased.

However, the optimum depth of applied water was determined 106 mm for winter wheat in the water limiting situation by the mentioned method (Equation 18.13); thus, the area irrigated as deficit irrigation is 2.9 (1/0.34) time of full irrigated one. Equation 18.13 shows that the optimal depth is not a function of volume of available water (Figure 18.5). In Table 18.5, the values of A and I_n versus the different values of V for optimal depth of applied water (106 mm) and full irrigation are shown. According to Table 18.5, relation of I_n (for optimal depth of applied water)/I_n (for full irrigation) is 1.51 and the ratio of A (under optimal depth of applied water)/A (under full irrigation) is 2.96.

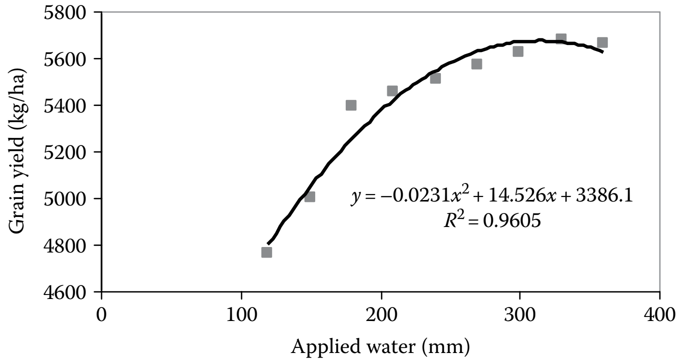

FIGURE 18.3 The grain yield function of winter wheat.

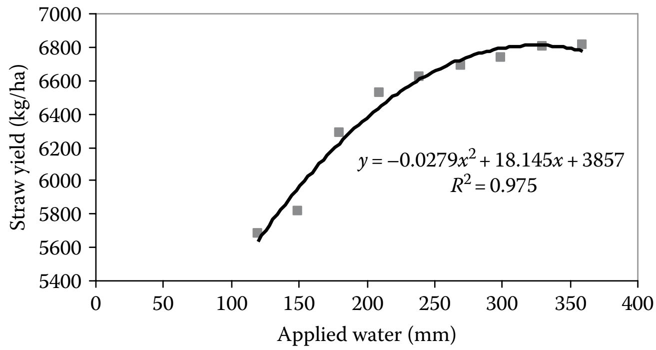

FIGURE 18.4 The straw yield function of winter wheat.

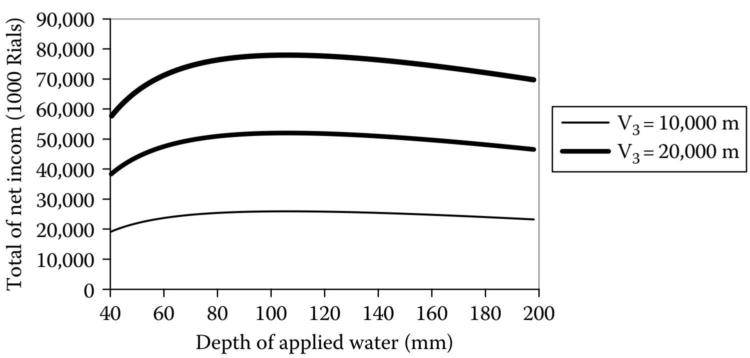

FIGURE 18.5 The functions of net income for different values of available water supply.

18.3.2 Case Study 2: Application of Every-Other Furrow Irrigation

The experiment was conducted on potatoes (Marfona cultivar) at the center of agricultural research of Shahrekord, Iran in 2004 [28]. The experiment design was a randomized complete block with four replications and three treatments of the furrow irrigations: (1) every-furrow irrigation or normal method (*N*) in which the water has been applied to every furrow; (2) fixed every other-furrow irrigation (*F*) in which the water has been applied as fixed to every other furrow throughout the growth season; and (3) variable or alternative every

TABLE 18.5 Comparison between Full and Deficit Irrigation

V (m^3)	A (ha) at Deficit Irrigation	I_n (1000 Rials) at Deficit Irrigation	A (ha) at Full Irrigation	I_n (1000 Rials) at Full Irrigation
10,000	9.4	25,983	3.2	17,188
15,000	14.2	38,974	4.8	25,781
20,000	18.9	51,965	6.4	34,376
25,000	23.6	64,957	8.0	42,970
30,000	28.3	77,948	9.6	51,563
35,000	33.0	90,939	11.1	60,157
40,000	37.7	103,931	12.7	68,751
45,000	42.5	116,922	14.3	77,345
50,000	47.2	129,914	15.9	85,939

other-furrow irrigation (V), which is similar to F, but the water has been applied to the furrow, which was dry in the previous irrigation cycle. Therefore, there were 12 plots in which there were 6 furrows 10 m long and 0.75 m spacing. The irrigation interval was 7 days and the amount of water for each irrigation was determined by measuring the soil water content in the root zone by gypsum block before irrigation and raising the soil moisture to the field capacity. The volume of irrigation water was measured by a counter as shown in Table 18.6 (runoff was zero). Potato was planted having a distance of about 0.3 m in the rows and 0.1 m deep on May 25, 2004. Nitrogen, phosphorous, potassium, and micro fertilizers were applied prior to planting and during growing season based on the requirements. Potato yields were harvested on September 26 in the same year. The yields were weighted and the water use efficiency was determined for each plot.

The average water use efficiencies (WUE) were 620, 744, and 710 g (dry mass) per cubic meter and 2.87, 3.38, and 3.23 kg (wet mass) per cubic meter for N, F, and V treatments, respectively. The WUE values are shown in Tables 18.7 and 18.8. The analysis of variance shows that there is a significant difference

TABLE 18.6 Irrigation Scheduling

Irrigation No.	VF[a]	VPN[b]	VPE[c]	VT[d]
1	0.55	3.3	3.3	39.6
2	0.36	2.16	2.16	25.92
3	0.41	2.46	2.46	29.52
4	0.48	2.88	2.88	34.56
5	0.56	3.36	1.68	26.88
6	0.6	3.6	1.8	28.8
7	0.58	3.48	1.74	27.84
8	0.53	3.18	1.59	25.44
9	0.51	3.06	1.53	24.48
10	0.49	2.94	1.47	23.52
11	0.48	2.88	1.44	23.04
12	0.44	2.64	1.32	21.12
13	0.4	2.4	1.2	19.2
14	0.39	2.34	1.17	18.72
15	0.38	2.28	1.14	18.24
16	0.34	2.04	1.02	16.32
Sum	—	45	27.9	403.2

[a] Volume of water entry to one furrow (m^3)
[b] Volume of water entry to one plot with every other furrow (m^3)
[c] Volume of water entry to one plot with normal furrow (m^3)
[d] Volume of water entry to total farm (m^3) = (4) ∗ 8 + (3) ∗ 4

TABLE 18.7 The Results of WUE (Based on Wet Mass, kg/m^3)

Replication	Treatment *N*	*F*	*V*
1	2.47	3	3.19
2	2.98	2.95	3.08
3	2.91	3.73	3.15
4	3.13	3.84	3.48

TABLE 18.8 The Results of WUE (Based on Dry Mass, g/m^3)

Replication	Treatment *N*	*F*	*V*
1	499	669	722.2
2	598.5	632.1	653.8
3	628.8	758.2	691.4
4	758.3	916.6	773.9

(significance level of 5%) between WUE (dry and wet) under the three treatments. Therefore, WUE in *F* treatment is more than *N* and *V*. However, it can be concluded that every other-furrow irrigation with normal water irrigation has a significant effect on WUE.

18.4 Summary and Conclusions

Deficit irrigation practices differ from traditional water supplying ones. The main objective of the deficit irrigation is to increase the water use efficiency of a crop by eliminating the irrigations that have little impact on yield.

The optimization models maximize the net income and the application efficiency and minimize the total costs. Therefore, it is needed to make the production function of the crops and to model the simulation of the advance phase in surface irrigation. This model gives the design variables for surface irrigation including inflow discharge, time of cutoff irrigation, length of the furrow or border irrigation, and the percent of deficit irrigation in relation to full irrigation.

The every other-furrow irrigation is one of the methods of deficit irrigation in furrow irrigation. It is concluded that the fixed every other-furrow irrigation method highly increases the water use efficiency in comparison with the other methods including every-furrow irrigation and variable every other-furrow irrigation methods.

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19

Drought Mitigation Practices

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Abstract Basic drought mitigation practices have involved policy or institutional, physical, technological, and socioeconomic actions. Apart from individual efforts, community, regional, and national-based efforts are common and are often in larger-scale applications than the individual efforts. This chapter is based on the expository review of existing studies and documentations. Studies have indicated that water management practices in developing countries are fraught with the challenges of increased population pressure on land and water resources, poor education and poor awareness of drought mitigating principles, poverty, limited government intervention, and limited community-based actions. The National Drought Management Plans and the documented provisions on best practices for drought management appear to be well thought and can be useful if implemented across drought-prone areas. The chapter provides insights into various practices across the world and concludes that although the level of the implementation of drought mitigating plans varies, many people in developing countries are still severely affected by drought. It is recommended that efforts should be geared toward institutionalizing local drought management practices that have been found effective among communities. Incentives for scientific research on early drought warning system and enhanced coping systems among the poor people are also recommended.

19.1 Introduction

Review of the existing studies on drought has indicated that scientists do not yet agree on its precise definition. This is probably because drought occurrences are typically multifaceted; despite the fact that drought conditions often generally indicate lack or paucity of water supply, such paucity of water supply vary locations and are characterized by use-differential thresholds. While studies [20] defined drought as a temporary meteorological event, which stems from a deficiency of precipitation over an extended period of time compared to some long-term average conditions, others [5,35] have defined drought in terms of water-shortage effect on human livelihoods. Brammer [5], for example, argued that drought is a period when the supply of soil moisture is less than what is required for normal crop growth.

Common types of drought are meteorological, agricultural, hydrological, and socioeconomic droughts [20]:

1. Meteorological drought is linked with dryness occasioned by absence or below average intensity, frequency, or amount of rainfall, over a period of time and location.
2. Agricultural drought is defined as a condition of paucity of moisture within the expected threshold requirements for a particular crop over a period of time.
3. Hydrological and socioeconomic droughts are linked with water shortages for different hydrological importance such as streamflow and socioeconomic uses, respectively.

In general, drought can be termed "the less-than-useful availability of water for a particular use in any environment." Drought conditions are associated with famine, hunger, malnutrition, diseases and food insecurity, and deaths [34,42].

Although drought conditions have been recorded in almost all parts of the world, at a particular time or the other, the residents of developing countries are often worse hit by its effects. This is probably because the coping strategies in these countries are often weak [42]. For example, in a sample of 210 small-scale farmers in part of southwest Nigeria, Nevo [27] reported that

- More than 88% indicated that they change the date they planted their crops to reduce loss from late rainfall and prolonged dryness.
- About 70% did not have measures against the effects of excessive rainfall and heat.
- About 20% of the farmer indicated loss of farm land to excessive rainfall, another 28% to excessive heat, and 32% to windstorms.
- About 72% practiced mulching to cope with excessive heat and prolong dryness.
- Practice of irrigation was limited as less than 2% practice it.
- About 16% of the farmers use industrial fertilizer.

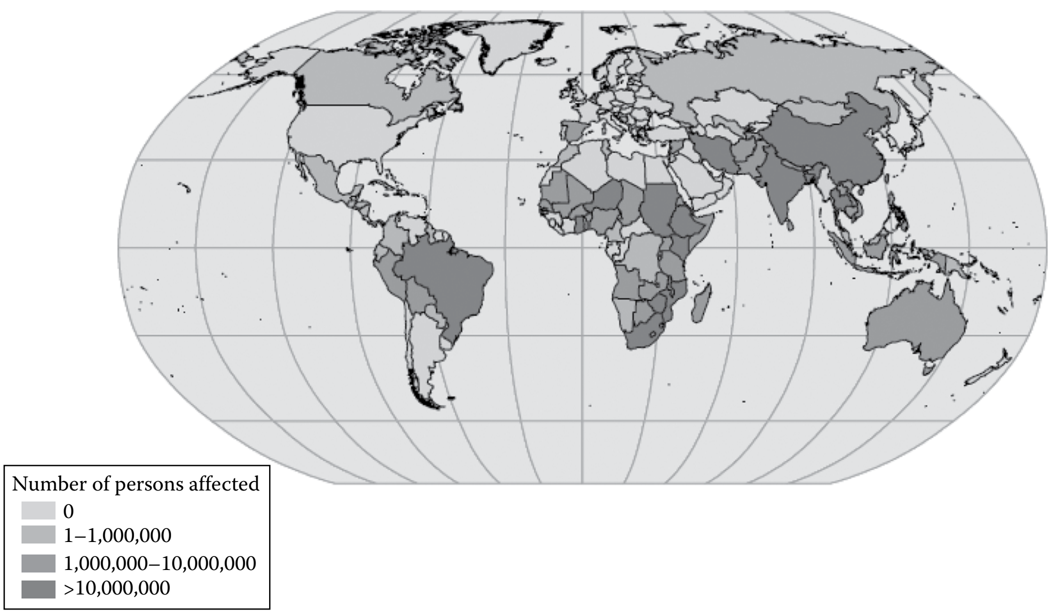

FIGURE 19.1 Spatial distribution of drought hazards between 1970 and 2008. (From EM-DAT International Disaster Database, www.emdat.be.)

The map produced by the Centre for Research on Epidemiology of Disasters for 1970–2008 also indicated that many countries in Asia, Africa, and South America recorded more victims than those in Europe and North America (Figure 19.1). More casualties have been recorded in the Sahelian drought of the 1970s and the East African drought of 2010–2011 (which alone displaced more than 13 million people and killed many others) than droughts in Europe or North America [34]. This is, however, not to underestimate the effects of North American and Australian droughts that caused human and animal displacements and deaths, but to note the effect of the varying level of drought management practices and available infrastructure in drought-response measures in these affected countries.

Drought is an important global challenge, because the causative factors—climate and anthropogenic—are transboundary [9,22]. The actions of reducing the severity, seriousness, or painfulness of drought are referred to in this chapter as drought mitigation practices. The chapter is divided into sections, focusing on definition and types of drought management practices, characteristics, existing framework, and problems associated with drought management practices.

19.2 Drought Mitigation Practices: Definition and Types

Drought mitigation practices are methods or techniques and practical means for achieving ecosystem sustainability in the period of the drought-related dryness. The goal of drought mitigation practices is to cushion the hazardous effects of drought on humans, livelihoods, and other environmental components. Studies indicated that drought mitigation encompasses three vital components: drought intensity assessment and monitoring; drought declaration and prioritization of areas for drought management; and development and implementation of drought mitigation strategies [18,23,38]. Mitigation practices can be explained in three forms—the pre-disaster, during disaster, and post-disaster practices—and can be classified as proactive and reactive measures [7].

19.2.1 Pre-Disaster Mitigation Practices

The purpose of the pre-disaster mitigation practices is to enhance preparedness and mitigation actions. These mitigation practices are generally proactive [7]. The need to enhance drought preparedness and mitigation actions has evolved because of the reports of increased frequency of droughts in different parts of the world. Most measures that are targeted at these actions are related to integrated soil, water, and forest management and they form parts of soil conservation, watershed development, and forestry programs in many countries. Proactive measures are those attempts to mitigate the future effects of drought occurrences, including the development of an early warning system, augmentation of water supplies, demand reduction (such as water conservation programs), and crop insurance [4,7,23].

In some regions, drought-proofing measures are taken before the crop is planted and drought management measures are taken during the crop growing period including in situ conservation, reduction in plant population, supplemental irrigation, etc. Preparedness suggests pre-disaster activities designed to increase the level of readiness and improvement of operational and institutional capabilities for responding to a drought. In practice, drought prevention and preparedness involve water supply augmentation and conservation (e.g., rainwater harvesting techniques), expansion of irrigation facilities, effective dealing with drought, and public awareness and education. Enhancing these actions as suggested by the document on best practices [35] often include

- Developing drought response measures that reinforce the concept of risk management as a key element of a national drought management policy
- Promoting training opportunities to enhance the understanding of how seasonal forecasts and decision support tools can be applied by vulnerable groups and within vulnerable sectors to improve resilience, coping capacity, and preparedness

- Identifying incentives that could be provided to vulnerable sectors/groups to enhance the adoption of risk-based management measures in support of a national drought management policy
- Identifying and communicating successful examples of how interagency or interministerial coordination has enhanced drought monitoring, mitigation, response, and planning
- Examining how drought drills or exercises could be effectively used to promote more effective institutional coordination for preparedness and response
- Collecting local and traditional knowledge and incorporating it into the decision-making process
- Ensuring connections between science and policy aspects

In practice, most actions for preparedness in many developing countries have not successfully tamed the effects, probably because of inaccurate or ineffective drought monitoring and early warning systems (EWS) [40]. Studies describe the early drought warning system as a system of hardware, software, and expertise for data collection, processing, manipulation, analysis, and information presentation for decision support for an impending drought occurrence [4,26,29,40]. An adequate EWS should provide information about the onset, continuation, and termination of drought confditions in support of drought planning [8]. An EWS requires adequate means, capability, and will early response for effectiveness [29].

19.2.2 In- and Post-Drought Mitigation Practices

Common mitigation practices, worldwide, are emergency response and relief measure, which can be classified as reactive measure [7] are typically in-drought practices while others including low-interest loans, transportation subsidies for livestock and livestock feed, provision of food, water transport, and drilling wells for irrigation and public water supplies [4,7] can be in- or post-drought practice, depending on when they take place. Emergency responses can reduce losses during drought conditions, if authorities, individuals, and communities are well prepared, ready to act, and are well equipped with necessary infrastructure [18,29,30].

On the other hand, many in- and post-disaster mitigation practices, including provision of emergency relief in times of drought, have been criticized as inefficient, ineffective, and untimely [7,43]. Some studies have argued that the post-disasters' provision of relief may not promote self-reliance and may increase vulnerability to drought [6,43]. Problems can also arise where the victims do not trust the infrastructure providers. For example, in a study of a disaster handling in Nigeria, Omodanisi et al. [30] noted that most victims of disasters did not use the available infrastructure because of high medical costs, poor education, poor awareness, and distrust in government systems. They [30] noted that post-disaster measures were often grossly politicized.

As a guide to effective in- and post-disaster mitigation, the United Nations International Strategy for Disaster Reduction (ISDR) [35] indicated that a good practice of emergency response should involve

- Developing adequate linkages between early warning and relief and response
- Carrying out rapid assessment of ongoing drought emergencies
- Preparing diagnostic tools for rapid assessments
- Establishing and training interagency diagnostic teams (pre-emergency)
- Conducting research that evaluates the effect of drought relief measures on societal vulnerability

19.3 Some Characteristics of Drought Mitigation Practices

A large number of studies exist on the practices of drought management across the world. Table 19.1 shows a list of the typical effects of drought and mitigation practices, varying from rain-fed agriculture to school attendance, especially in developing countries. In Asia, drought mitigation approaches are initiated at national and community levels, and these are either pre- or post-disaster measures. In a post-drought (*Rabi and Kharif*) situation in part of Bangladesh, Habiba et al. [20] reported that mitigation practices included emergency provision of drinking water, food grains and food subsidies, and food-for-work

TABLE 19.1 Some Effects of Drought on Human Livelihoods and Mitigation Practices

Livelihood	Impact	Mitigation Practices
Rain-fed agricultural production	Reduced or no yields; increases in extreme events and accelerating trends on the productivity of rain-fed agriculture	Imports (short term); choosing to sow different crops or do not sow at all (short term); application of improved agronomic practices (i.e., no tillage)
Irrigated agricultural production	Reduced yields; vulnerability of water resources; reduced water quantity; water quality	Water rationing; water allocation review; sowing dryland crops; introduction of water banks for temporary transfer of water rights
Livestock production	Weight loss; mortality; destocking; increase in incidence of diseases; lower fertility and reproduction rates	Destocking; feed distribution; cattle parking/relocation of herds; nomadic migration; use of special reserved areas (stock routes and stock reserves)
Water	Degraded water quality; surface water shortages; overdrawing and depletion of groundwater; increased competition and conflict over water	*Ex ante* identification of supplemental and alternative sources of water; technical optimization of water resources; enactment of water laws and rules
Environment	Ecosystem degradation; loss of biodiversity; species migration and extinction; landscape change and wind erosion; increased risk of wildfires; fisheries impacts	Maintenance of environmental flows
Transportation	Reduced transportation and navigation on rivers and lakes	Preparation of alternate transportation plans using rail and road ways
Health	Morbidity and mortality increase; increased incidence of suicides; incidence of wind-, dust-, and vector-borne diseases and respiratory illnesses; degradation of sanitation; decreasing levels of nutrition, depression, trauma, and suicide; increased use and dependence on drugs and alcohol	Food supplements; stockpiling food; more robust social safety nets; improved access to mental and physical health care; access to counseling services
Tourism and recreation	Loss of recreation areas; decline of tourism revenue; reduction in taxes collected	Improved management of water reservoirs; reallocation of water supplies between user sectors
Energy	Decreased hydropower production; brownouts and blackouts; increased demand; destruction of transmission lines	Energy restrictions; improvements in efficiency; alternative energy supplies; diversification of energy sources
Society	Migration and loss of community; decreased marriage rates; increased divorce rates; increased incidence of suicides; increased conflicts; loss of assets and reduced property values; increased theft and crime; impacts on traditional cultures and practices; gender inequality; migration of population of farm/rural areas to urban areas	Social protection and cash-transfer programs; diversification of rural livelihoods; employment programs and schemes; provision of counseling services
Education	School dropout rates (short term); lower school enrollment (longer term)	Targeted social protection; mid-day meal schemes to prevent school dropouts
Cost of emergency response programs	Amount spent on relief and response	Insurance schemes, better targeting of response programs; improved monitoring of impact sectors to identify when measures should be implemented to mitigate impacts
Secondary and tertiary impacts on economic productivity	Loss of income and productivity; opportunity costs; higher personal debt levels	Employment guarantee schemes and loan waivers

Source: Andreu, J. et al., Drought planning and management in the Júcar River Basin, Spain, in: Schwabe, K. et al. (eds.), *Drought in Arid and Semi-Arid Regions*, Springer, Netherlands, DOI:10.1007/978-94-007-6636-5_13, 2013.

programs to the affected parts of the country by the government. The Bangladesh government also offered the employment to the population affected by drought and helped to mitigate the drought severity [20]. In some cases, the government, research institutes, and nongovernmental organizations in drought-affected regions initiated modern agricultural technology and practices such as high-yielding variety seeds, increased irrigation coverage, and introduced drought-tolerant crop varieties. In general, drought management involves the participation from individuals, nongovernmental organizations, and government institutions.

The role of the government in drought mitigation practices includes the provision of institutional framework to coordinate the activities of individual, communities, and nongovernment mitigation attempts. Policies and provisions of the United Organizations [36] documented key elements of desirable mitigation practices at national levels to include the following:

1. Promoting standard approaches to vulnerability and impact assessment
2. Implementing effective drought monitoring and early warning systems
3. Enhancing preparedness and mitigation actions
4. Implementing emergency response and recovery measures that reinforce national drought management policy goals
5. Understanding the cost of inaction

In Europe, effects of socioeconomic and meteorological drought in parts of the nineteenth and twentieth centuries were mitigated with the coordination provided by the European Union policy; including the Water Framework Directive (WFD) 2000/60/EC [14] and "Blueprint to Safeguard European Waters" [2,13]. The WFD was designed to support member states in achieving good ecological status for the water bodies within their river basin districts and protect them from pollution [3]. The WFD also provides general criteria for assessing the impact of drought on water bodies through the enhancement of the activities of River Basin Management Authorities with programs and plans to deal with particular aspects of water management [3,12,13].

In addition, the effects of agricultural droughts (e.g., at Ebron Basin and Riegos del Aragon projects in Spain, and at San Joaquin Valley in California, United States) were mitigated through irrigation systems. Irrigation systems are aimed at enhancing the production of food crops and managing water transfers and purchases in water stressed and scarcity communities [16,37]. In parts of Africa, Hassan [21] argued that provisions of water resources through dam construction can be a long-term drought management practice, which can be preferred to the short-term practices of water and food aids. In South African, Hassan [21] and Hassan and Craford [22] reported that previous drought impact was mitigated through the construction of an extensive network of dams, large water storage capacity, as well as the development of a comprehensive interbasin water transfer infrastructure to move water from surplus to deficit regions. In other parts of Africa, management practices involving water supply through dam construction and river basin management have been fraught with duplication of functions (with other government-owned organizations), inconsistent government policies, population increase (with capability for increased demand), and sabotage [1,11].

Furthermore, an important characteristic of mitigation practices, especially among the rural dwellers, is indigenous knowledge. Indigenous knowledge can be defined as a local knowledge that is unique to a given culture or society, the systematic body of knowledge acquired by local people through the accumulation of experiences, informal experiments, and intimate understanding of the environment in a given culture [24,39,41]. Nyong et al. [28] noted that integrating indigenous knowledge to mitigation and adaptation practices in areas that are characterized by recurrent droughts, such as the Sahelian part of Africa, could substantially increase the resilience of the people. Traditional knowledge about how local populations have coped with previous droughts also has the potential of providing important guide for addressing current and future drought challenges [8].

In addition, a number of studies have shown that digital technologies, including geographical information system (and its data acquisition system—remote sensing and digital surveying) and social media networks (such as Facebook, YouTube, Twitter, and others), have become very important in information dissemination [25,31,33,34]. Studies have used geographical information systems (GIS)—a system comprising hardware, software, digital database, algorithms, and people (users and expert) for data collection, organization, storage, analysis, retrieval, and information presentation for solving an earth-referenced problem—to map drought hotspots, vulnerability, and assess the impact of a decision or policy [4,10,34]. Data sources for drought information system include multi-date satellite imagery, topographical maps, information from published and unpublished sources, and ground (coordinate) data [31]. Social media are Internet-based applications that enable people to conduct online communications intended for interaction, community input, and collaboration [42]. The use of social media makes it possible for disaster-related information to be shared in real time, enabling people to obtain information without the slightest time gap. And as mobile devices become widely available and social media gets increasingly popular, citizens can easily receive and report real-time disaster events surrounding them [34].

19.4 Framework for Drought Mitigation Practices

Diverse opinions are listed in the literature as frameworks for drought mitigation practices, based on the scale (individual, community, regional, or national) of practice. Wilhite [41] provided an outline of a 10-step policy approach for mitigation practices, which advises a sovereignty to establish a National Drought Management Policy (NDMP) (Figure 19.2). The NDMP is to define mitigation goals and procedures from the experience of stakeholders and relevant organizations. Most NDMP tend to achieve better when community participation is involved [20]. In addition, adaptive mitigation strategy—involving learning from the indigenous knowledge—appears to have been more successful than the structural, government-planned projects that are often devoid of community participation [20]. This is probably because drought occurrence can be difficult to predict trends, and therefore tackling their impacts will be uncertain with physical parameters, whose measurements can take a relatively long time to perfect [15,17,19]. Figure 19.2 also showed the Hyogo Framework [35], which describes the need for strong political commitment, community participation, and consideration of local realities and indigenous knowledge, knowledge transfer, and ensuring effective and affordable practices for effective mitigation practices. A review of preparedness in previously drought-affected areas indicated that many stakeholders have the responsibilities in ensuring adequate mitigation practices (Figure 19.3). Apart from individual efforts, community-, state-, and/or national-based efforts are common and are often in larger-scale applications than the individual efforts.

19.5 Problems with Drought Mitigation Practices

A number of problems have been associated with drought mitigation practices, and these are more noticed in developing countries. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change [32] identified financial and technological constraints, human resources and physical barriers, integrated water resources management, synergies with other sectors, and access to new varieties of crops, among others as key constraints to the implementation of climate adaption programs. A major problem with some developing countries is the problem of poor infrastructure to supply energy and provide adequate information to the people, as well as a high level of illiteracy. The Hyogo Framework for Action (Priority 3) recommended the need for awareness-raising and educational initiatives to help people make informed decisions. The recommendation is premised on the four important principles, namely, the effects of drought can be substantially reduced if people are well informed and motivated toward a culture of disaster prevention and resilience; effective information management and exchange requires strengthening dialogue and networks among disaster researchers, practitioners, and stakeholders in order to foster consistent knowledge collection and meaningful message dissemination; public awareness programs should be designed and implemented with a clear understanding of local perspectives and needs, and promote engagement of the media to stimulate a culture of disaster resilience, including

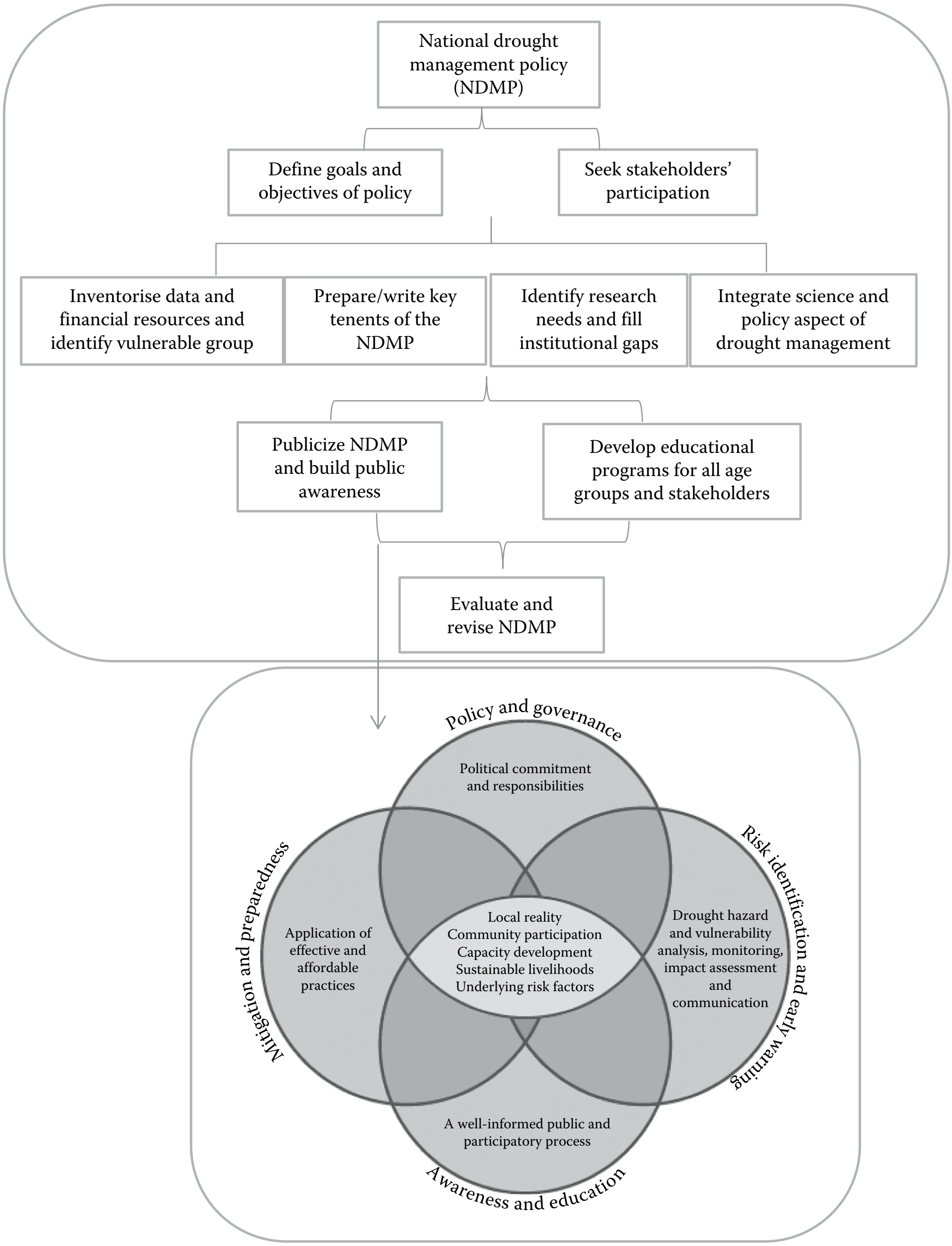

FIGURE 19.2 An organized approach for strong mitigation practices.

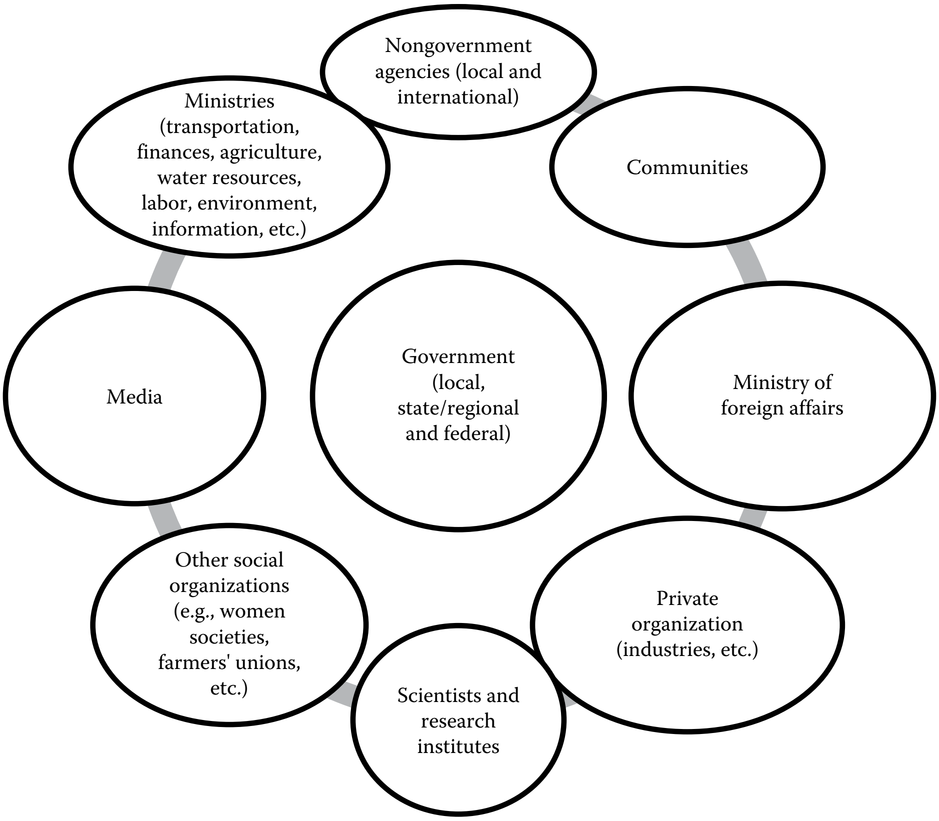

FIGURE 19.3 Some stakeholders in drought mitigation practices.

resilience to drought and strong community involvement; and education and training are essential for all people in order to reduce local drought risk.

Furthermore, climate, population increase, and urbanization are factors that usually exert pressures on available water resources. The studies have also shown that impacts of political instability and civil unrest in some countries may have worsened the capacity to practice sustainable water use [44]. In a recent study on adaptation strategies to the effects of extreme weather conditions in southwestern Nigeria, Nevo [27] found that over 70% of the small-scale farmers had secondary school education or less and earned at most 100,000 naira (less than US$500) per annum. Only about 2% of the farmers practiced irrigation as an adaptation method to agricultural drought because the farmers considered irrigation to be expensive.

19.6 Summary and Conclusions

This chapter is focused on drought mitigation practices. Basic drought mitigation practices have involved policy or institutional, physical or technological, and socioeconomic actions. The chapter is based on the expository review of existing studies and documentations. Studies have indicated that water mitigation practices in developing countries are fraught with the challenges of increased population pressure on land and water resources, poor education and awareness of drought mitigating principles, poverty and limited government intervention, and community-based actions, among others. The National Drought Management Plans and the documented provisions on good practices for drought mitigation appear to be well thought and can be useful if implemented across drought-prone areas. The chapter concluded that although the level of the implementation of drought mitigating plans and documents varies, many people in developing countries—where the awareness, climate education, and implementation of adequate drought management policies are relatively poor—will be severely affected by drought, if efforts are not geared by their government and nongovernmental organizations toward institutionalizing and nationalizing such plans.

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20

Social Impacts of a National Drought Policy in Australia

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Abstract Australia's drought policy history demonstrates how governments have attempted to accommodate different needs resulting in mixed political messages that fluctuate between a risk management approach demanding farmers to be self-reliant and an approach where financial support is provided during drought. These financial provisions undermine the risk management aspect where policy impact and rhetoric are constantly misaligned. We draw on previous research on national drought policy to focus on the local social impact of a national policy. A case study is used based on an irrigated agricultural production region in northern Victoria, Australia, to illustrate how drought is context specific, and particularly in rural areas where irrigation is used drought policy needs to be viewed with water policy. Tensions around the national policy translate to confusion at the local scale. The government is reliant on irrigated agriculture for export and farmers are being told they are valued as producers for the nation but the drought and water policy implications do not support this. Smaller-scale farmers are exiting agriculture as changes in policies compound the effects of climatic extremes. With Australia-wide evidence on the complexities of a national policy at local scales, the drought policy has been reformed to include welfare payments and self-reliance instruments in the same policy. Whether this will be the solution to manage drought in a vast country where climate change is predicted to increase the intensity and duration of drought is yet to be seen.

20.1 Introduction

Drought, as discussed in other chapters, takes different forms and effects different countries and regions of countries in varying ways. Globally, nations are searching for policies that can address these varying impacts but policy at a national level inevitably takes a general approach that can overlook the socio-economic and cultural issues in pursuit of universal management solutions. While Botterill and others (see [16,17,19]) have written extensively about drought policy in the Australian context, this chapter draws on their research to focus on the local impact of national policy. We describe and analyze the social impact of drought policy at a finer scale to emphasize the local and regional consequences of a national policy. In doing so, we illustrate how the impact of drought is context specific and, noting that in many instances in rural communities, drought policy cannot be considered in isolation from other policies such as those associated with agriculture and water. Since first writing this chapter, there have been further changes to both drought and water policy in Australia which are not addressed in this paper but which implicate farmers and their communities. However, the general trends discussed in this chapter appear 'locked-in' in material terms.

Australia is often referred to as the land of extremes and has one of the most variable rainfall climates in the world [24]. Australia is the driest inhabited continent with the lowest amount of runoff and the lowest percentage of rainfall as runoff [66]. The country is prone to drought and drought has been part of the history since nonindigenous settlement (Table 20.1). Drought is quite distinct from other natural occurrences. It is a slow onset event making the beginning and end problematic to define. Because of this, it is more difficult to garner public support than it is for more immediately devastating events such as fires and cyclones. Each drought has specific characteristics where some may last for years and others can be short and intense.

Drought is also distinct in the number of definitions it has—it is dependent on the location (what is "normal" in terms of precipitation for the area in question), the time of year it occurs, how long it lasts, and the activities of that area. As stated in previous chapters, drought has been defined in meteorological, hydrological, agricultural, and socioeconomic terms [74]. Defining drought in the context of a continent like Australia is challenging because it is a vast nation. It contains six different climatic zones based on temperature and humidity [22] and six based on the Köppen classification system, classified on the distribution of key vegetation, rainfall, and temperature [23]. Therefore, for any definition of drought to be practical it needs to be both regionally and operationally specific [52]. Overcoming this barrier is one of the most challenging aspects for mediating the social impacts of drought—it highlights the tension between the intention of policy and the local temporal and spatial reality.

TABLE 20.1 Major Droughts of Australia

1864–1866	Severe in Victoria, South Australia, New South Wales, Queensland, and Western Australia.
1880–1886	Southern and eastern states affected.
1888	Areas in Victoria and Tasmania, New South Wales, Queensland, South Australia, and Western Australia.
1895–1903	Most of Australia affected but most persistently the coast of Queensland, inland areas of New South Wales, South Australia, and central Australia.
1911–1916	Victoria (1913–1915); Tasmania (1913–1915); New South Wales, particularly inland areas; Queensland; Northern Territory; South Australia; and Western Australia (1910–1914).
1918–1920	All of Australia except some areas in Western Australia.
1939–1945	New South Wales (severe on the coast), South Australia (persistent in pastoral areas), Queensland and Tasmania, Western Australia, Victoria, and central Australia.
1958–1968	Central Australia and vast areas of adjacent Queensland, South Australia, Western Australia, New South Wales, and northern Australia were affected, with varying intensity, 1957–1966; and south-eastern Australia experienced a severe drought, 1964–1968.
1972–1973	Mainly eastern Australia affected.
1982–1983	Eastern Australia severely affected.
1991–1995	North-eastern New South Wales and Queensland.
1997–2009	Especially eastern and Western Australia.
2012–2014	Queensland and New South Wales; areas of Western Australia.

Source: Australian Bureau of Statistics, Yearbook Australia 1988, 1988, viewed June 9, 2014, http://www.abs.gov.au/AUSSTATS/abs@.nsf/lookup/1301.0Feature%20Article151988; Bureau of Meteorology (BOM), Drought statement archive, Australian Government, 2014, viewed June 9, 2014, http://www.bom.gov.au/climate/drought/archive/.

On average, a severe drought occurs in some part of Australia around once in 18 years [25]. The Commonwealth Scientific and Industrial Research Organisation (CSIRO) [32] warn that Australia may experience up to 20% more drought months in the next 20 years (where historical rainfall data are used to determine what is "normal" for each area).

All definitions of drought have some elements in common, but Botterill [11] maintains that what characterizes drought is the effect it has on human activities. In Australia, these effects have been mostly determined through impacts to agricultural production (with ongoing research around rainfall timing, distribution, and deficiency; see [73]) and producers. This needs to be considered in the context of Australia's settlement history where the intention of the federal and state governments through legislation from the 1850s onward was to establish an agrarian population [45]. The vastness and differences in pastoral and agricultural activities across the country became evident early on.

Agriculture at the start of the twentieth century was considered the cornerstone of national wealth and accounted for 19.3% of Australia's gross domestic product (GDP)—the largest single sector with manufacturing and mining trailing [5]. The towns were being built as service centers around agriculture, factories were springing up, and Australian farmers were encouraged to see progress and so used the latest advances in technology to overcome climate (typically experienced as drought). The harshness of the land was continually exposed through salinity, rising water tables, and soil quality where extensive vegetation clearing for agricultural settlements further exacerbated soil erosion [9].

Even though the country had been oriented for pastoral and agrarian production, at the beginning of the twentieth century focusing on the production of food for empire, Australia has always been developing its cities. Initially, the cities provided the markets for production and then the ports for production export: now the cities dominate the political and social landscape of Australia [53]. As Australia currently positions itself as a primary producer for Asia, the increasing disconnect between rural and urban regions expands, with urban prosperity seeming to depend on exports from the increasing isolated rural and regional landscape. The social consequences of national identity politics like those associated with these apparently endlessly accelerating export imperatives have significant consequences for these rural regions and their ecological and political realities.

With agriculture playing such a large role early on for Australia's gross domestic product, technical solutions needed to be found to deal with the climatic extremes of the country. Damming commenced in Australia in the mid-1800s as with the number and capacity of dams continually increasing to try and meet demand [63]. The need to, and the belief that it was possible to "drought-proof" areas to reduce the risk for agriculturalists, became a colonial political issue and Alfred Deakin, who later was the second prime minister of Australia, was a strong advocate for technical modernity, including irrigation and damming. By 1900, the combined storage capacity of major dams (those with a capacity over 100GL) to provide the necessary storage for irrigation was 250 GL. In a 40-year period (1900–1940), the capacity was 35 times greater at 8730 GL. In 1990, this figure was 87260 GL—10 times that of 50 years previously [63]. Eighty-seven percent of the storage capacity for major dams was constructed after 1950 (in 1950 agriculture had increased to represent 30% of Australia's GDP [5])—technology was trailing the demand for climate proofing (and for energy production). On-farm dams demonstrated the extent that farmers understood the necessity of preparing for an uncertain climate; and by the twenty-first century, it is estimated that across Australia there are more than two million farm dams, with a total storage capacity of about 8000 GL [8]. These technical responses to drought parallel the policy responses to drought.

20.2 Policy Response to a Natural Disaster

Australia has only had a National Drought Policy since 1992, but before this drought was understood as a natural disaster. In the Australian Constitution, the States have the responsibility for natural disasters where they can declare the event a "disaster" and once declared are responsible for providing financial assistance. The Commonwealth Government did not become involved with natural disasters until 1939 when they provided a grant to the Tasmanian government for bushfire relief [12].

The response to drought was ad hoc up until 1966 when the Commonwealth Government established the *State Grants* (*Drought Assistance*) *Act*, in which the Commonwealth matched State Government spending for each dollar for disaster relief. This was to assist Queensland and New South Wales specifically as both States were experiencing losses in agricultural production due to droughts at the time. In 1968, the Act was extended to South Australia and Victoria. From 1969, farmers were encouraged, through the introduction of incentives, to increase their economic reserves in good years—part of the Drought Bond Scheme through the *Loan* (*Drought Bonds*) *Act* 1969 [15].

Disasters activated a Commonwealth contribution to funding following the states provision of a base amount. In order to formalize these arrangements, the Commonwealth Government introduced the Natural Disaster Relief Arrangements (NDRA) in 1971, enforcing a minimum payment by State governments before the Commonwealth would contribute to funding. To this extent, the NDRA determined how costs would be distributed between the Commonwealth and States, even though the responsibility for pronouncing the "disaster" resided with the States. With different State's arrangements for drought, only some producers qualified for Commonwealth support creating tensions among producers in the same state, because of differences in weather conditions and between producers in different states, because of the different State's perspectives of government assistance [54]. This was one of the reasons leading to a review of the NDRA.

20.3 Drought Policy as a Progress Model

Drought perceived as a disaster came into question in the early 1980s, prompted by the severe and widespread droughts of 1982–1983 and the realization of the unsustainable increasing costs to governments [58]. Eventually, the Commonwealth Government announced in 1989 that drought would no longer be covered in the NDRA arrangements between the Commonwealth and States. Up until this time, drought had dominated the expenditure for natural disaster relief payments. Discussions were ongoing until 1990 when a Drought Policy Review Task Force (DPRTF) was established to revise the government's approach to drought policy. The DPRTF aimed to

1. Identify policy options, which encourage primary producers and other segments of rural Australia to adopt self-reliant approaches to the management of drought
2. Consider the integration of drought policy with other relevant policy issues
3. Advise on priorities for Commonwealth Government action in minimizing the effects of drought in the rural sector [54, p. 2]

The DPRTF [54, p. 2] argued that drought is a relative concept and not some absolute condition and therefore "represents the risk that existing agricultural activity may not be sustainable, given spatial and temporal variations in rainfall and other climatic conditions." This was the official recognition of a mismatch between production and ecology in some areas of Australia with an opportunity to reconsider how these could be aligned. It reinforced the idea that drought should not be considered a disaster while placing the risk management aspect of drought onto individuals. This was also about financial risk to the government. The DPRTF [54] found that it was no longer justifiable to include drought in disaster arrangements when drought had *always* (our emphasis) been part of Australia's variable climate. The reasoning emphasized that farmers, through their management practices, should be able to plan for and manage the impacts of drought in line with whole farm planning [54] where climatic variability is one aspect of overall land management. This devolution of responsibility to the local level by the Federal Government was an enormous change in drought management and policy [69] and the social implications consequent on these changes were to take a further 20 years to play out.

With the agreement of State and Commonwealth Ministers, an announcement of the National Drought Policy was made in July 1992. The objectives of the policy were to focus on "self-reliance" and "risk management" under conditions of climate variability. The mechanism to support the policy was through the revised Commonwealth Government Rural Adjustment Scheme, commencing in 1993. The Scheme shifted the rural policy focus from income support to support for improving productivity, profitability, and sustainability, implemented through instruments including interest rate subsidies on commercial borrowings, small grants for skills improvement, and financial planning advice aimed at those farmers that were assessed to have good long-term profitability potential [14]. This in effect defined self-reliance in line with the neo-liberal position dominating public policy [48]. At the same time, the Commonwealth government established the Farm Household Support Scheme targeting financially unviable farmers by providing them with income support for a limited time while they were exiting the industry. This explicitly connected agricultural modernization trends (larger scale, more efficient farms, risk management) with "drought proofing"—and became a *de-facto* social policy.

In 1993, the National Drought Policy came into effect—a time of drought in most of Australia. In the policy, "normal" and "severe" droughts were differentiated and "severe" was included in the "exceptional circumstances" (EC) clause of the Rural Adjustment Scheme [11]. The policy recognized that there could be occasions—"exceptional circumstances"—where the severity of the event was outside the scope of what could be considered good risk management. As areas of Australia were experiencing drought at the time, the "exceptional circumstances" clause needed to be operationalized almost immediately and it became evident that the declaration of "exceptional circumstances" would require more objective criteria [12].

This was rectified in 1994 when "exceptional circumstances" were defined through six criteria—meteorological conditions, agronomic and livestock conditions, water supplies, environmental impacts, farm income, and scale of the event [62, p. 6]. EC encompassed three main programs—interest rate subsidies (for commercial loans), a welfare payment, and farm management deposits (an income scheme where farmers could deposit pre-tax income for use in subsequent years). Because of ongoing drought in 1994, Drought Relief payments (income support) were made available to farmers in EC-declared areas.

> A major drought commenced in southern Queensland in 1991, intensifying in 1994 and 1995 [22]. At the time, it was the worst drought on record in Queensland in terms of agricultural production loss. In 1995, the then Labour Prime Minister Paul Keating addressed a Queensland Grain Growers Association Conference in Roma, a town at the center of the drought. This was seen as an unusual action for a Labour government to address a population, largely known as national party supporters. In his speech, Keating [38] declares: And I sincerely hope that they [the farmers] also know the Government knows the value of farmers. There are two ways to measure their value. You can do it with figures … The other way of measuring the value of farmers is by their contribution to the spirit of the country … They have endured extreme hardship and real despair…The toughness and spirit of Australia's farming families should be an inspiration to the rest of Australia. And that is one very good reason as good as their productivity and efficiency, as good as the value of their harvests why Australia's farming families must survive. They are essential to the national psyche.
>
> Some, I know, will not be able to stay on the land. But this Government is determined to see that the vast majority do.

This speech highlights not only the tension for farmers but tensions for the government when balancing the value of agricultural production for export and the cost of drought support for individual farmers and communities.

A change of federal government in 1996 to a liberal-national party coalition resumed discussions of what should constitute drought support. In 1997, the Rural Adjustment Scheme was abandoned and replaced by Agriculture—Advancing Australia. In this new scheme, the drought relief payment component was retained but under the name of Exceptional Circumstances Relief Payment [12].

There were a number of problems with EC from its commencement in 1992. The main criticism was the way in which areas were declared EC, defined by administrative boundaries rather than biophysical characteristics—meaning that neighbors with similar production systems could be in different EC zones—one declared EC and one not. There were also other eligibility criteria for individual farms within areas that had been declared EC, which raised questions around equity and farm management practices. There were also issues around the length of time to get approval for an EC application and the ensuing financial support [14]. Because of the issues, the drought continuing, and at least one area in Australia being declared "exceptional" since its inception, the Agriculture and Resource Management Council of Australia and New Zealand introduced new guidelines for EC in 1999. This declared that the event had to be "rare and severe; effects must result in a severe downturn in farm income over a prolonged period; and the event must not be predictable or part of a process of structural adjustment" [61, p. 93]). The National Rural Advisory Council (NRAC), an independent advisory body that assessed EC applications for areas, was established at the same time. The state and territory governments needed to compile and submit their EC applications to the Commonwealth Department of Agriculture Fisheries and Forestry who passed the applications to NRAC for further consideration. This added to the time to get an EC declaration for an area.

As various regions of Australia had been in drought since 1995, it was announced in 2008 that drought policy would again be reviewed with the focus once more reverting to self-reliance and risk management. The national review in 2008 announced by the then Minister for Agriculture, Fisheries and Forestry, Tony Bourke, included the following:

- An economic assessment of drought support measures by the Productivity Commission
- An assessment by an expert panel of the social impacts of drought on farm families and rural communities
- A climatic assessment by the Commonwealth Scientific and Industrial Research Organization (CSIRO) and the Bureau of Meteorology of the likely future climate patterns and the current exceptional circumstances standard of a one-in-20-to-25-year-event [33]

The Productivity Commission [61] assessment found that the farm management deposits were aligned with the risk management concept and could assist with defining self-reliance on farms; and this was more so than the other programs that added to debt or created welfare dependency [70]. The EC clauses meant that over time, the government response to drought had returned to one of crisis management rather than risk management.

The Drought Policy Review Expert Social Panel [42, p. 3] appointed to investigate the impacts of drought on rural communities found that "future policy should seek to move people towards an acceptance that future dryness will occur and is not a crisis." Again there was a move back to the idea of drought being "normal" and hence able to be planned for and perceived as manageable (although the report does recognize the hardship rural communities face in such instances). The climatic assessment conducted by the Bureau of Meteorology and CSIRO [47] found that drought will be more frequent and severe, especially in southern areas of Australia over the next 20–30 years and that the definition of "exceptional circumstances" was out of date. Based on these reports, the EC subsidy closed on June 30, 2012 [34]. The theoretical normalization of drought at a national level and associated with a recognition of changing climatic conditions tangentially called into question the historical realities of closer settlement that had previously reinforced smaller-scale agricultural settlement patterns. The implications of these changes are discussed more fully in the case study to follow.

These reports prompted a pilot of drought reform measures in Western Australia from 2010 until 2011—the Commonwealth government partnered with the Western Australian Government to "test measures designed to better support farmers, their families and rural communities in preparing for future challenges" [49, p. 1] to inform a new national approach. The different programs ranged from farm planning, business support, farm family support, farm exit support, and those that targeted the rural communities.

The Drought Pilot Review Panel [49] assessed the pilot and confirmed that it was appropriate to move forward with programs that focus on risk management but include social support in terms of income and services—this was a shift toward recognizing a "mutual responsibility" [49].

This change in focus was formalized in the Intergovernmental Agreement on National Drought Program Reform in 2013 [34]. The Program outlined arrangements to replace Exceptional Circumstances with the objectives being to

1. Assist farm families and primary producers adapt to and prepare for the impacts of increased climate variability [75]
2. Encourage farm families and primary producers to adopt self-reliant approaches to manage their business risks
3. Ensure that farm families in hardship have access to a household support payment that recognizes the special circumstances of farmers
4. Ensure that appropriate social support services are accessible to farm families
5. Provide a framework for jurisdictions' responses to needs during periods of drought [34, p. 2]

Within this program, there is a Farm Household Allowance provided to eligible farmers experiencing hardship—it replaces the Exceptional Circumstances payments and differs in that no EC declaration for the area is needed. Even though the Reform will not be implemented until July 1, 2014, ongoing drought conditions in Queensland and parts of New South Wales have also meant that the Government introduced an Interim Farm Household Allowance. The Farm Management Deposits Scheme will continue under the Reform but with a few enhancements to income thresholds. This scheme recognizes that the cash flow of farmers fluctuates between years so aims at assisting the farmers with building their cash reserves [35]. Prime Minister Tony Abbott, after visiting drought-stricken areas, declared "farming is a very significant part of our economy and will play a critical role in our economic future. This is a government determined to stand by the people of Australia in good times and bad" [59]. With both welfare payments and self-reliance instruments, it is too early to assess whether it will meet its objectives but this is an attempt to integrate household level support through the national recognition of drought.

It is inevitable when national policy tries to be relevant at a local scale that it comes up against the issue of multiple and different local scales. This results in further tensions at national and local levels as oversimplified solutions are massaged to fit all circumstances. What this history of national drought policies demonstrates are governments trying to accommodate different needs, but the outcomes reflect mixed political messages fluctuating between the provision of financial support in times of drought ("you can count on government" (as in the 1995 Keating speech and 2014 Abbott declaration)) and the demand for farmers to assume a more active role in managing for climate risk on farms ("the modern farmer incorporates climate risk as part of their farm management planning").

In Australia, as urban populations increase, production becomes more distanced from the urban centers with the rural context being less understood by urban voters who are convinced that the "farm is a business" rather than a more complex enterprise that incorporates land management and stewardship. Globalization, financialization, and ongoing commodification of water and land add to the tension in the local landscapes as deregulation of agricultural markets and increasing farm debt become both internal and external drivers of change. Agricultural production in the Australian landscape is at a crossroads after 180 years of the progress model, and drought, which has always been a part of this landscape, continues to exacerbate the decision processes around agricultural production systems for the future. While historically the rapid expansion of damming and irrigation were responses to the imperative for production in a drought-affected and water-limited landscape, the future drought, water, and agricultural policies are being determined now. And while the drought policy evolves, the farmers are dealing with climatic extremes, changes to markets, and increasing debts. In many places throughout Australia, smaller-scale farmers are exiting the industry as these compounding factors limit their capacity to continue farming. The following section uses a local case study to elicit these tensions on the ground.

20.4 Drought Policy in Context: A Case Study from Northern Victoria, Australia

In this section, we examine the impacts of drought, drought policy, and water policy in an agricultural case study to illustrate the complexities associated with national policy deployed at local scales. As the case study site is an irrigated production area, the water policy environment needs to be considered along with drought policy. The case study was part of research conducted from 2009 until 2011 in two towns in northern Victoria, Cohuna and Rochester (Figure 20.1). The sites are in different local government areas (LGAs) and different irrigation districts but interconnected as part of the Murray–Darling Basin (MDB). The basin is a large area of Australia (14% of land [6]) containing two major rivers—the Murray and the Darling with many tributaries running off.

In the 1870s, a series of Land Acts in Victoria opened up land in northern Victoria to selectors with the yeoman (small-scale family farmer) promoted by the governments of Australia. These land selection acts were “designed to promote an agrarian society and opportunity for the ‘poor man’ and the ‘yeoman’” farmer [72, p. 449]. Small-scale agriculture as practiced in Europe was adopted in Australia to meet subsistence needs as well as providing economic opportunities through the sale of surplus agricultural production. Less than 10 years later, this initial idea was inconsistent with the broader picture of agriculture and the government’s intention that agriculture provide food for Empire—this larger goal required larger scale and market-oriented enterprises [51]. Farmers not only required more land but enough capital (for extra skilled labor and technology) if they were to make farming successful. The government however, intent on creating a yeomanry, through the *Victorian Land Act 1869* reduced the upper limit of land holding sizes to 320 acres, despite recommendations to increase it. Critics of this Act and the Settlement Acts that followed frequently cited the differences in rainfall, soil

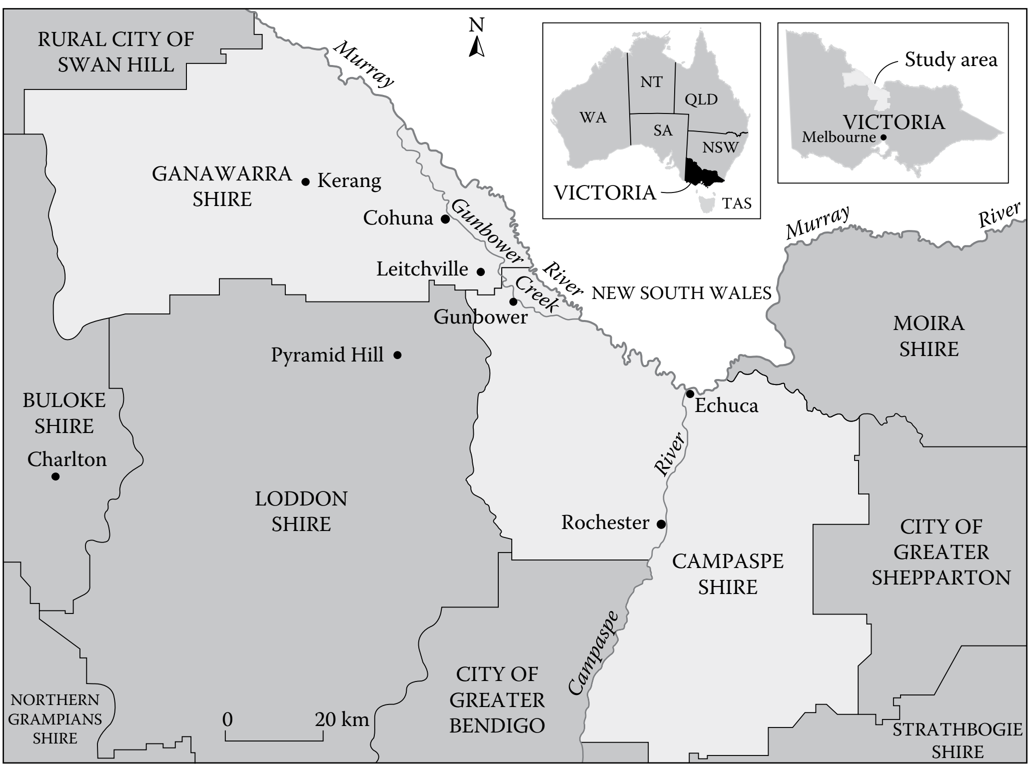

FIGURE 20.1 Case study sites—local government areas in northern Victoria.

type, and skill level between England and the new land but all of these criticisms were largely ignored [10]. One of the selectors wrote to the Argus newspaper (the daily newspaper for Victoria's capital city) stating that

> The object of the Government has been stated to be to encourage permanent settlement and residence on the land, after an ideal of a British yeomanry. It has, however, been proved that the small selection system will not do this, and probably it is impossible it should do so at present, nor for the next 50 or 100 years. (*The Argus*, 30/4/1881)

These Land Acts were created and enacted in urban centers, far removed from the rural landscape where the realities of the land size, soil quality, and weather extremes exposed the contradictions. The financial viability of these new agricultural enterprises was an everyday tension from the start of nonindigenous settlement.

Because drought was recognized as being a barrier to agriculture in early settlement, irrigation schemes were privately set up in the late 1800s, with government taking over in the early 1900s. The case study towns trialed different agricultural and horticultural products over time (including crops, stone fruit, cauliflowers, herbs, lettuce) but due to problems with the water table rising and subsequent salting of the soil, many industries were not suitable. Consequently, agricultural production in both areas became predominantly irrigated dairy [44].

From the late 1800s until the present time, there has been a recurring theme of drought, and this, coinciding with other factors such as economic recessions, has led to the rationalization in agricultural industries resulting in increases in farm size and production accompanied with ongoing small-scale farmer exits [46,55]. These exits correspond with the federal policy, which focuses on agricultural production as an export commodity (only 3% of Australia's GDP in 2009/2010 [3]). This is in stark contrast with the speech made in 1995 by the then prime minister who declared: "It is one of the great challenges of the next decade or so: to see that the 100,000 or so farming families of Australia are not replaced by a thousand or so companies" [38].

The remainder of the case study focuses on the most recent drought that began in 1998 in the area. The year 2002 was the driest winter on record and the irrigation season started 1 week earlier than usual [21]. EC became operational in both study sites in 2002. Some of the often cited problems of EC as discussed in the previous section became evident in the local community. It caused tension among farmers because some secured assistance in the form of interest rate subsidies and welfare payments while others did not. Anecdotal evidence indicates that local businesses (not eligible for EC but supporting farmers with extended debt lines, for example) also found the subsidy inequitable and this led to further strain in community relationships. In 2008, the interest rate subsidy was extended to businesses in drought-affected communities through the *Farm Household Support Amendment Bill 2008* (*Cth*), which extended "the eligibility criteria for the Exceptional Circumstances Relief Payment to include the operators of small businesses that are located in towns that are substantially reliant on farm income, have a population of 10,000 or less and are wholly or partially located in an Exceptional Circumstances declared area." The EC subsidies were intended to assist with everyday business, but the administrative aspects of it compounded the tension in these local communities.

Exceptional circumstances subsidies were not the only drought support in the communities at the time. From 2002, due to the severity and extent of the drought, extra drought assistance was provided by both Commonwealth and state governments. The Commonwealth Department of Agricultural Fisheries and Forestry (DAFF) provided extra measures in the budget for drought including Country Women's Association Emergency Aid Fund; drought-affected areas—interim support; drought assistance—Exceptional Circumstances declarations; and personal counseling services for drought-affected communities in rural regions [29]. Another "extreme" drought year in 2007 resulted in additional funding in the 2007–2008 budget to "fund professional advice for farmers in severe difficulty, to subsidies management training and education and to provide re-establishment grants to assist those who wish to exit the industry" [31]. Even though there were different peaks of funding, the drought was ongoing from 1998 meaning individual and community pressures were increasing.

The Victorian Government through its emergency relief triggers [40] also provided extra funding for drought assistance and drought relief programs that spanned a wide range of initiatives including training, counseling, welfare, business subsidies, and community events. Within the funding, local governments were given grants for community engagement in planning and regional adjustment. How these funds were used in the study sites is described in the following text.

Both sites appointed drought coordinators with the State government funding. Their purpose was to work with local communities to help lessen the social, economic, and health impacts of the drought. The drought coordinator's responsibilities were to ensure community members' access to information and providing links into service agencies and government departments to obtain support, assistance, and advice for locals affected by drought. Coordinators from both sites lived in the communities and were familiar with local conditions. They had existing relationships with local organizations and individuals, including farmers. The drought coordinators were the impetus to start drought committees (DCs) that connected the local, state, and national scales. These committees consisted of representatives from state and federal government departments from agriculture, environment and health, non-governmental organizations (NGOs) (particularly around community support), local businesses, and farmers. The purpose of the DCs was to initiate a social recovery process for communities. Meetings were held regularly to discuss and approach drought issues from varying perspectives and to determine how to best target funding.

One of the programs that attracted statewide attention was the "Farm Gate" initiative. It was an outreach program where the drought coordinator and a rural support officer (RSO) (funded by the Commonwealth Department of Agriculture Fisheries and Forestry (DAFF)) would drop in on farms with an information pack detailing available services for drought-affected farms and families. Farmers were made aware of services such as rural financial counseling that they could access to help them with farm management planning during the drought or to discuss exit options. The rates of depression in these communities were high and the Farm Gate program also aided in referrals to health services. The success of this program is associated with the number of people that were visited—estimated to be 300 farms in 3 years (about 70% of farms) in Campaspe Shire and more than 70% of rural properties in the Gannawarra Shire [20]. Due to privacy laws in Australia, documenting issues around depression and suicide is problematic but these visits helped unmask the extent of the mental and social impact of drought.

The coordinator roles continued for 7 years but both State and Commonwealth funding ceased on July 1, 2009. The State gave assistance through the Department of Planning and Community Development and the Commonwealth, through DAFF, provided funding for the RSO positions [30]. The Campaspe Shire Council was unable to continue the drought coordinator position without the additional funds. The Gannawarra Council recognized the importance of the coordinator role so their resources were combined to continue the position on a part-time basis from July 1, 2009 to March 2010. This was the seventh year of EC declarations in the area. Even though the Gannawarra Shire Council Drought Social Response and Recovery Plan [43] outlined the importance of the position continuing until 2012, resources at the local level were not available. The local governments lobbied State and Commonwealth governments for further financial assistance but were unsuccessful. The initial funding from the higher levels of government was intended initially to help with social recovery—but this process had not begun when the funding ceased due to the length of the drought. As community resources had been depleted over the previous 12 years, it would take some time for the community to be self-reliant again. Even though the community through active support networks tried to employ the goals of self-reliance and risk management, after many years of drought, the challenges of meeting these goals became apparent—lack of both financial and human capital limited the types of plans that could help the community move forward.

Some of the NGOs receiving funding from the State government employed extra staff during the drought to service the communities by providing social support networks, including food aid. As funding was aligned with Commonwealth and State budgets, longer-term work positions and programs could not be assured due to the uncertainty associated with funding allocations. Many positions were therefore temporary, and because of their stop-start nature coinciding with funding cycles, the staff in these positions described their work efficiency as being undermined as work arrangements became more fragmented. The programs and positions ended up being controlled by the funding rather than vice versa [72].

The rural financial counseling service, subsidized by the Commonwealth government, had a major role providing business advice to farmers during the drought. As funding decreased from 2009, the amount of staff and hours dedicated to these roles decreased substantially in the study areas. This was a time, both psychologically and financially, when farmers needed this extra assistance and advice to determine their future strategies.

Discussions at the Commonwealth level began in 2010 regarding the cessation of EC in drought-affected areas, as weather wise the drought broke in many areas in early 2010 [26]. In the study sites, the decision was made to withdraw EC from March 2011. The Victorian Department of Primary Industries (DPI) appealed the decision to withdraw EC for the Gannawarra and Campaspe districts arguing that due to the extent of the drought followed by damaging floods [56], there was no opportunity for farmers to get back to normal production. This argument was not accepted by the Commonwealth Government as NRAC when reviewing conditions stated that "improvement in seasonal conditions has provided the majority of producers across the area with the opportunity to return to typical farm management practices" [56]. On this advice, EC was withdrawn as proposed. The consequences on ground were complicated. After 10 years of drought and increasing debt, followed by excessive flooding and the subsequent management issues consequent on drought and flood, many farmers despaired [71].

As both communities rely on irrigation for production, drought policy cannot be considered in isolation from water and water policy. Agriculture is the biggest consumer of water in Australia and 2009–2010 accounted for 52% of total water consumption [7]. Up until 2000, agriculture accounted for approximately 70% of water consumption, but since the last drought, this has decreased to approximately 50% [67]. The value of irrigated agriculture, although declining in recent times, still accounts for 29% of the total value of agricultural output in 2009–2010. In terms of agricultural land, irrigated land makes up less than 1% of all agricultural land in Australia. Sixty-one percent of this irrigated agricultural land is situated in the Murray–Darling Basin [57]. In the study area in northern Victoria, under the most extreme climate change scenarios but depending upon the catchment (or watershed), total inflows may be reduced by 42%–72% and water available for consumptive use may be reduced by 10%–67%. These are significantly variable changes that make it imperative to plan on farm for water "security" but almost impossible to be certain that it is possible to do so. Environmental water was reduced by 51%–86% [39]. Environmental water is "water used specifically to maintain the health of river, wetland and estuarine ecosystems, particularly during periods of drought and low flows" [41]. Changed climatic conditions are also predicted to accelerate soil degradation and loss of soil fertility [28]. These factors may see a reduction in food production in Australia by over 15% [60]. The Australian government relies heavily on irrigated agriculture in Australia for its export market predictions. In the study region, the incompatibility of drought and water policies is confusing for farmers. How climate change will impact water availability and policies about future water allocations increases the uncertainty in this region.

In the research areas, farmers can own permanent entitlements to water right allocations (which they pay for each year) and a rural water corporation that manages water storages in northern Victoria determines the amount they can access each irrigation season based on water storage levels. The year 1997 was the first year that water allocations for irrigators were reduced and was a sign of things to come. In 2002–2003, one of the worst drought years, water allocations were reduced to an all-time low where temporary water trading became prevalent. Farmers were seeking assistance from State government water and agricultural staffs to understand how they could better manage their water allocations. With ongoing drought, more farmers increased their reliance on the temporary water market but in 2006–2007, another severe drought year, temporary water prices were the highest ever, which significantly limited options for farmers. To put this in context, between 2001–2002 and 2009–2010 there was a 1.6 billion liter decrease in raw milk production in Victoria—1.3 billion liters of this decrease occurred in northern Victoria (severely affected by drought conditions) due to their reliance on irrigation water. The region went from being the highest to the lowest milk-producing region in Victoria during this time [37]. At the time of the research, there were still many farmers who were deciding their future, and what their decisions meant for the community as a whole is still unclear.

From 2007, there were a number of other issues playing out in the water policy environment at both the federal and state levels that had an impact on how the farmers were able to respond to drought and how this would affect their future options. In 2007 (the second part of a 50-year plan set out in a white paper, "Securing our water future together," for water management in the State [68] as a response to drought), the Victorian Government introduced water unbundling. "Unbundling" is the process where water is no longer attached to the land title, which means that farmers can sell their water to get access to cash flow and theoretically buy it back at a later stage. Many farmers chose this option after 8 years of drought. However, there were other discussions in the northern Victoria irrigation area. Modernization of the irrigation system was another strategy in the Victorian government White Paper to increase water security and water use efficiency. The project is to upgrade existing infrastructure and to eliminate some of the smaller channels, which would effectively dry out the farms on those channels. Farmers not attached to the main channels were asked to "consider discontinuing" from irrigated agriculture. However, the land is not suitable for dryland farming, and without water attached to the land, the land has no value. As the modernization proceeds, farmers' choices are to fund private irrigation, cooperative irrigation, or to leave.

At the federal level, there have been many discussions about how the Murray–Darling Basin should be best managed, an extra concern for the farmers in the case study region. The Basin spans four states and one territory where the Commonwealth government, through the *Water Act 2007*, introduced "a strategic plan for the integrated and sustainable management of water resources in the Murray–Darling Basin …based on the best scientific, social, cultural and economic knowledge, evidence and analysis" [57]. In 2010, where ongoing drought was one factor, the plan was reviewed. This was a lengthy process and the plan was signed into law in November 2012, with implications for irrigation practice. A new Water Recovery Strategy for the MDB has reassessed the method of water recovery and now prioritizes infrastructure investment over water buybacks [36], although Adamson and Loch's [1] analysis of this approach suggests that farmers will be more exposed to debt and the environment will not benefit. The exact implications of the Basin Plan [50] and the associated strategies are largely unknown but they do add an extra layer of complexity and uncertainty in future planning, especially when future drought is factored in.

Farmers in this area have been responsive to government policies. It was the Land Acts that established these marginal areas for settlement and deemed them suitable for agriculture. Aside from the supporting technology in terms of irrigation, when this was not sufficient to ensure production, there were policy interventions in the form of drought subsidies at an individual and community level. These technical and policy interventions have been aimed at maintaining productivity levels. With the overlay of the changes to water policy and the subsequent modifications to allocation amounts and timing, the misalignment between the landscape ecology and the agricultural production demands is being recognized. The message coming from the government now is that there is insufficient water in the rivers to both maintain a healthy river function and compensate for drought conditions by supporting highly intensive agricultural production industries. The water policy, as the drought policy, fluctuates between trying to maintain agricultural productivity and acknowledging the tension between the production and environmental conditions in the same landscape.

20.5 Drought Policy Disconnected from the Ecological and Social Realities at the Local Scale

A "national" drought policy assumes some kind of uniformity, which as shown in the case study example is not a universal social or ecological reality in Australia. The complexities of each area cannot possibly be considered through a uniform policy. In its latest forms, drought policy is still problematic. Botterill and Hayes [18, p. 148] sum up the lessons from 20 years of drought policy in Australia stating that "drought declarations that are tied to agricultural support programs become politicized and contested." Australia's national drought policy is shown as inconsistent in time (from risk management to a crisis management approach providing welfare assistance returning to risk management and self-reliance focus) and space (different declarations for adjoining areas based on legislative boundaries and not the ecological characteristics). This type of policy is not responsive to local conditions, and as Stafford Smith [64] points out one of the goals of drought policy should be for on-ground practices and policy systems to both evolve with changes in their environments. This is not possible unless the local context is considered and it is only then that a national context may be able to progress more constructively over time [65]. There needs to be a longer-term approach to both the policy and what this means for local-scale agricultural production and land management in the future. In Australia, the departments responsible for drought policy and water policy are different—problematic when irrigated agricultural production represents a significant proportion of overall agricultural output. Australia's federal system of the government complicates policy and can mean that different approaches actually conflict between departments and between federal and state governments, impeding their effectiveness [11]. In the Productivity Commission inquiry [61], attention is drawn to irrigation drought being the new "unknown" creating even more uncertainty. This is increasingly becoming the reality for those farmers (particularly small-scale farmers without the economic means to have flexibility in water markets) in irrigation districts.

A recent study in one of the irrigated production areas of the Murray–Darling Basin found that effective government support for drought needed to include "collaboration between service providers and practitioners; undertaking community-led projects and programs; supporting proactive, consistent and long-term approaches to service provision" [2, p. 298]. This is consistent with our findings and also with the Victorian Government, which states that one of the principles in designing measures for drought assistance was that "drought related assistance should target household welfare and community resilience through support for social and economic infrastructure" [61, p. 394]. However, as described in the case study, withdrawing funding at a crucial time when social recovery was not yet underway hampered the collaborative efforts of the community-led, local-based projects and their limited resources.

Whether a new drought policy can overcome these tensions is yet to be determined, but there is promise that the importance of a whole community approach will be considered. However, a decentralized approach to drought subsidies creates tensions with the centralized, productivist meta-narrative of the government. There, markets have been deregulated and water commodified so Australia can continue its historic focus as an agricultural export nation.

As Botterill [13] stated, if policy outcomes are to be viewed in relation to the values they stand for then economic efficiency needs to be clearly acknowledged as a value. "There is no single objectively correct drought policy for Australia—any combination of policy measures will privilege one value over the others" [14, p. 63]. As in the case study example, the small-scale farmers are decreasing in numbers and being forced off their farms as water is commodified and long-term policy rules change. This is confusing when farmers are told via the media and political reporting that they are valued as producers, for their nation, but somehow this value is a short-term economic consideration.

Australian drought history shows that there has been a constant misalignment between policy impact and rhetoric [18]. The case study here confirms this statement. It began with the definition of drought as disaster changing to a risk management approach, but the EC provisions in the new drought policy quickly undermined the risk management aspects of the policy. The changes stemming from the Drought

Policy Reform, implemented from July 1, 2014, which are a combination of a risk management approach with a welfare safety net, will be the continuation of Australia's drought policy story. Theoretically, the approach allows more scope for recognition of the local and social impacts of policy. How this plays out on the ground will be seen during the next drought.

20.6 Summary and Conclusions

Drought has consistently been a part of Australia's settlement history with different regions experiencing different impacts. How to manage this through a national policy has been a constant challenge for the Government that fluctuates between adopting a risk management approach demanding producers be self-reliant through preparing for and managing climate risk to supporting agricultural production through financial provisions with accompanying discourse around valuing Australian farmers. In irrigated rural communities, drought policy needs to be considered with water policy where there is also constant change—both associated with inconsistencies between rhetoric and policy implications. For farmers trying to adapt to a long-term drought, changes in drought and water policy during drought impeded longer-term strategies to manage climate risk as the changes created uncertainty around available finance and forthcoming water allocations. Even though the communities through social support networks provided assistance, ongoing drought required external assistance from governments to continue local support. Extra financial assistance was provided to the local governments but withdrawn at a time when communities needed to embark on a social recovery process to try and rebuild their self-reliance capacity. This once again confused the sentiment behind the policies and whether farmers were expected to pursue irrigated agriculture in these regions. The latest reform to drought policy recognizes the differences in local contexts and proposes a balance between providing financial assistance and promoting risk management. The on-ground effects will not be known until the next drought and whether the policy lasts another political cycle is yet to be seen.

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21

History of Drought Management in Australia

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Abstract Australia's rainfall climate is one of the most temporally variable in the world, and drought is a common climatic phenomenon in many parts of the country. While it poses significant risks, drought has also driven significant innovation and adaptation over the history of human settlement in this "sunburnt country." Based on this experience, Australia has developed high-level research expertise in understanding climate systems and, increasingly, the drivers of climate variability. It is also one of the few countries to have legislated a national drought policy aimed at managing drought risk.

This chapter provides an outline of the key factors influencing drought conditions in Australia and traces Australia's experience in dealing with drought and its impacts. It discusses the ongoing evolution of Australia's national drought and water resource policy and provides examples of adaptation measures in agricultural production systems and urban settings. While there remains room for improvement, Australia's experience indicates that enhanced understanding of climate systems and skill in climate forecasting plus good policy, governance, and planning are essential to drought preparedness and drought risk management.

21.1 Introduction

In Australia, as in other parts of the world, drought is a common climatic phenomenon causing significant social, economic, and environmental impact [37,91,107]. However, perhaps uniquely, drought in Australia has also driven significant adaptation. Australia's agricultural production systems operate under a high level of uncertainty in terms of climate variability [82] and are renowned as some of the most resource-efficient, globally [25,65]. Australia has developed high-level research expertise in understanding climate systems and, to some extent, the drivers of drought [66,123]. It is also one of the few countries to have legislated a national drought policy aimed at managing drought risk [16,123].

This chapter provides an overview of Australia's drought history, the ways in which drought risk and associated water scarcity have been managed over time, and the impact of drought on Australian landscapes, production systems, and communities. It looks at responses to drought from prehistorical evidence of Aboriginal Australians' land use systems developed over thousands of years, through the challenges faced by European settlers in modifying conventional farming systems and adapting to the extremes of climate variability over the last 230 years, to current-day drought risk management and regional, state, and national governance around mitigating the impact of drought events and managing water scarcity. It starts by considering the role that research has taken in enhancing the understanding of the geophysical systems that influence climate variability, including drought, in Australia and concludes by considering the challenges Australia will face under future climates.

21.2 Drivers of Climate Variability and Drought Risk in Australia

Australia's current climate is recognized as one of the most temporally variable rainfall climates with the world's highest levels of year-to-year rainfall variability [82]. Streamflow variability in Australia is also higher than that reported for most other parts of the world [29]. For most of its recent geological history, much of Australia has been subject to episodes of prolonged and severe drought interspersed with wet periods and often widespread flooding [111]. These extremes are naturally occurring components of Australia's climatic variability [123].

Climate variability occurring in the past 120 years or so—that is, during the period of instrumental records of rainfall, atmospheric pressure, and sea surface temperatures—has been related to coherent large-scale processes occurring at low frequencies in the ocean and atmosphere. While local processes, including those driven by vegetation and mesoscale convection, affect rainfall in Australia [42,43], it is the recurring nature of these large-scale drivers and their effect over large areas that make their influence more clear and quantifiable.

Many large-scale drivers of climate variability in Australia have been identified. The primary driver of interannual rainfall and temperature variability is the El Niño Southern Oscillation (ENSO) [8,87]. ENSO is a quasi-periodic, coupled global atmospheric–oceanic phenomenon, which occurs when sea surface temperatures in the eastern Pacific Ocean are anomalously warm. Such events often result in below-average rainfall anomalies in Australia [100]. The effect is strongest in monsoonal regions where typical El Niño warm events are linked with drought conditions across much of Australia and Indonesia, with the reverse occurring during La Niñas [6,81].

The effect of ENSO on Australian rainfall has varied over the historical record [8] due to changes in the nature of ENSO and also the influence of teleconnections with other large-scale drivers of Australian rainfall. Research over the past 15 years or so has refined the broadscale relationship between ENSO and rainfall, identifying seasonal and regional nuances and the nonlinear responses of rainfall to ENSO; for example, El Niño events do not always produce droughts [129,132]. In southeastern Australia, the El Niño years of 1982 and 2002 were years of severe drought, yet 1997 had close to average rainfall [21]. These El Niño years can be categorized into different types of El Niños based on different patterns of sea surface temperatures across the Pacific Ocean; however, the differences in rainfall response to El Niño are still not readily explained.

Although ENSO is the dominant driver of interannual climate variability in Australia, there are other influences such as the tropical sea surface temperatures in the Indian Ocean as quantified by the Indian Ocean dipole index (IOD) [12,98,116,129]; the Antarctic oscillation, also known as the southern annular mode (SAM), which is the primary mode of variability in the midlatitude mean sea-level pressure [56,61,63,126]; fluctuations in the latitude and intensity of the midlatitude high-pressure belt [135]; the Pacific decadal oscillation (PDO), which is the first empirical orthogonal function (EOF) of North Pacific monthly sea surface temperature variability [85,109]; and climate change, the lowest-frequency component [40,99]. The effects of these vary depending on the specific region and time period considered.

These drivers modulate the characteristics of the higher-frequency rain-bearing synoptic features and consequently the Australian climate. The dominant synoptic influences in northern Australia are the monsoon trough (the intertropical convergence zone), tropical cyclones, the surface heat lows and associated troughs, trade winds, and onshore flow. In southern Australia, the dominant synoptic influences on rainfall are the east coast cyclones (a feature in the subtropical latitudes), low pressure, and frontal systems and cutoff lows.

The influence of the different drivers on rainfall varies geographically across Australia [115]: ENSO has the strongest effect on the winter and spring rainfall in eastern and northern Australia, extending through summer in the north; the IOD influences winter/early spring rainfall in southern and western Australia; and the SAM affects rainfall in all seasons in Australia's southeast and southwest but is weakest in autumn. On a monthly timescale, a single driver accounts for less than about 20% of the variance for most regions in Australia. The exception is spring rainfall in northern and southeast Australia where ENSO accounts for 30% of the variability, extending up to 50% in small patches.

These broadscale climate drivers are also strongly interconnected with each other, especially the tropical modes of variability ENSO and IOD [23,115]. ENSO is also the driver that is most strongly correlated with other drivers (e.g., Suppiah [125]; Wright [138]; Carvalho et al. [27]; Behera et al. [15]; England et al. [47]; L'Heureux and Thompson [78]; Williams and Stone [135]). The relationship between rainfall and ENSO also varies on a multidecadal timescale (e.g., Nicholls et al. [101]; Power et al. [108]) with greater coherency of Australian rainfall with ENSO apparent during cool phases of the Pacific decadal oscillation/interdecadal Pacific oscillation (PDO/IPO) [81].

Research into one of the most severe droughts in Australia's instrumental history, the so-called Millennium Drought or the "Big Dry" between 1997 and 2009 in southeastern Australia [52,131], has furthered knowledge on teleconnections between large-scale drivers and drought. All the major twentieth-century droughts (Federation Drought 1895–1902, WWII drought 1937–1945, and the Big Dry 1997–2009) in southeastern Australia appear to be caused by variability in the IOD, not ENSO [129]. During these droughts, the IOD has been either positive or neutral, driving a decrease in moisture advection into the region and, hence, decreased rainfall [115]. However, the severity of the Big Dry also appears to be linked to an increase in air temperature [99,129] and may also have been significantly influenced by SAM [131].

In addition, climate change is likely to change the features of drivers and also the teleconnections between them and rainfall [24,68,129]. For example, Cai et al. [24] suggest that global warming will increase the frequency of extreme positive IOD events from one event every 17.3 years in the instrumental record to one event every 6 years in the twenty-first century. It will also likely change the characteristics of drought [99], with the increase in temperatures increasing the severity of drought. Rainfall deficits may be similar to previous years of drought; however, increased evaporation due to warmer temperatures may mean that droughts are more severe.

In summary, while ENSO is the dominant influence on drought occurrence in Australia, other climate drivers also cause significant climate anomalies and significantly influence the effect that ENSO may have on rainfall. The relationship between rainfall and these drivers is nonlinear and is also being altered by climate change. Better understanding of the drivers of climate variability is critical to predicting the probability of climatic events such as drought and enhancing the climate risk decision-making and management needed to support resilient social, ecological, and production systems.

21.3 Australia's Drought History and a Brief History of Drought Management in Australia

As already discussed, the incidence and duration of drought over the 120-year period of recorded observations in Australia vary from seasonal to multiyear to decadal. In the last one hundred years, Australia has suffered six major droughts and at least twice as many less severe droughts [52,129]. These limited time series data have been supplemented from historical documents and palaeoclimatic records to produce a multiproxy (ice cores, tree rings, coral sequences, and documented records) timeline of climatic conditions dating back to the first European settlement of Australia in 1788 (e.g., Gergis [51]; Gergis et al. [54]). In addition, indigenous history and knowledge about past weather and climate changes in Australia, dating back thousands of years, increasingly contributes to better understanding of Australia's climate and its inherent challenges [59,64].

21.3.1 Prehistory Australia

21.3.1.1 Drought Experience

Australia has an extensive history of human occupation, extending back some 40,000–60,000 years [20,59]. This period saw both significant environmental change and climatic variation. A number of lines of palaeo-evidence suggest that environmental conditions indicative of extreme moisture variability, including drought and increasing aridity, emerged in Australia during the mid- to late-Holocene some 5,000 years ago [88,111,136], while ENSO-like patterns similar to those currently observed established some 3,000 years ago [50]. Climatic changes during the Holocene, which drove both the drying and increasing fire-proneness of Australian landscapes and vegetation [79,139], were potentially exacerbated by Aboriginal land management practices such as "fire stick farming" [19,48]. Ecological changes associated with the drying landscape were likely also linked to the extinction of the Australian megafauna and particularly the loss of large grazers through this period [55,70].

21.3.1.2 Drought Management

Prehistoric Aboriginal Australian populations were strongly impacted by climatic variability and varied both spatially and temporally [136]. Nevertheless, they persisted through time [83] and were, by inference, broadly successful in adapting to the increasingly harsh and variable Australian environment. By the time of European colonization of Australia in the late eighteenth century, their relationship with the land and use of resources was nuanced and responsive to environmental conditions [9,30,57]. They had a detailed understanding of the interactions between weather, water, and the landscape [30,57], and it is probable that their survival was underpinned by, both, their knowledge and use of climate refugia [57,122], their ability to manage their environment through methods such as strategic burning [19,48], and by social systems that ensured the mobility of populations [30,86,136].

21.3.2 Colonial Australia

The apparent lack of evidence of either permanent settlements or recognizable systems of land ownership or management in Aboriginal Australia [92] promoted the British concept of Australia as *terra nullius* (a land belonging to no-one). The colonization of Australia from the 1780s onward saw the displacement of Aboriginal populations and the imposition of both European systems of property rights and land management over much of temperate and semiarid Australia. However, while the ENSO climate cycle has been a major influence on life in Australia from the first days of European settlement [51], we know relatively little about the pre-twentieth-century climate history of Australia or how the first European settlers coped with drought or climate variability in general [51,54].

21.3.2.1 Drought Experience

Early records from the first settlement at Port Jackson (Sydney) indicate that, during the first years of the new colony following the arrival of the First Fleet in January 1788, erratic weather conditions severely hampered the establishment of agriculture [51,97]. By late 1791, drought conditions led to water restrictions, rationing of dwindling food supplies and the construction of "holding tanks" cut into the sandstone banks of a small spring-fed stream supplying the frontier township of Sydney [51]. Reconstruction by Gergis and Fowler [53] of El Niño and La Niña events over the past 500 years confirms the occurrence of a very strong La Niña event between 1788 and 1790, followed by a strong El Niño year in 1791 in a characteristic ENSO "phase flip" (e.g., Whetton and Rutherfurd [133]; Allan and D'Arrigo [7]).

21.3.2.2 Drought Management

As the European colony grew, sheep and cattle became the mainstay of Australian agricultural production systems and pastoralism was the dominant land use throughout much of the nineteenth century [57]. The spread of pastoralism across Australia's rangelands, in days prior to the establishment of private-property rights, was opportunistic [86] and "squatters" and their herds/flocks of livestock were often at the vanguard of the expansion into new territory. Access to water was critical to their survival and intense and violent battles over water sources occurred between Aboriginal owners and British settlers on the Darling River floodplain in the 1830s [57]. Pastoralists subsequently benefited from Aboriginal Australians' knowledge of the land, particularly as many were later employed as stockmen [57]. These pioneering "selections" were initially large (often the size of small European countries); stocking rates were low and livestock were moved within and between holdings according to rainfall and the availability of forage [86]. An extensive network of traveling stock routes (TSRs) also developed across eastern Australia in the early 1800s to enable the "droving" or "overlanding" of livestock to and from markets and between properties [117]. In many cases, these developed along traditional Aboriginal pathways used for travel, ceremonial and trade purposes, following the most accessible routes through the landscape, avoiding natural obstacles and connecting food and water sources [118]. Such flexible management systems were financially and potentially ecologically sustainable in the context of Australia's spatially and temporally variable rainfall [86].

21.3.3 Federation and Early-Twentieth-Century Australia

The vast pastoral holdings of the early colonial period were eventually broken up as competition for land increased; these were replaced by a system of family-run properties, although many of these ultimately proved too small to be economically or ecologically viable [86]. The closer settlement and more intensive land management associated with these changes saw the broadscale clearing ("opening up") of native vegetation to facilitate pasture growth; by the late 1800s, these changes in land cover also saw significant loss of biodiversity and alteration of natural ecosystems [13,119], along with critical changes in the hydrology of landscapes [10,22,62] and intensification of regional rainfall variability [42,43]. Politically, the federation of Australia in 1901 contributed to a range of new legislation with separation of responsibilities between the Commonwealth of Australia and the states for sectors such as agriculture and natural resource (e.g., water, mineral resources) management.

By the early part of the twentieth century, a significant increase in Australia's agricultural production occurred, driven by the discovery of groundwater in the Great Artesian Basin and expansion of pastoral activities across much of inland Australia, as well as technological advances including more productive grain varieties (e.g., William Farrer's rust-resistant "Federation Wheat"), increasing mechanization (e.g., Australian inventions including the "stump-jump plough," "scrub roller," and combine harvester), and advances in livestock breeding. With a small population, production exceeded demand and Australia became one of the world's major food exporters. By 1936, while Australia produced just 3%–4% of the world's wheat, it accounted for 18% of world exports, reflecting the high exposure of Australian farmers to the risk associated with international markets [2].

21.3.3.1 Drought Experience

This increase in agricultural production occurred against a background of significant climate variability and an increasing recognition of this inherent characteristic of the Australian environment, epitomized, in the words of a much-cited poem by Dorothea McKellar written at the time (1908), as a land "of droughts and flooding rains." The first two decades of the new century were characterized by a series of droughts, which had a major impact on livestock numbers. For example, the "Great Drought" (also known as the "Federation Drought") between 1895 and 1902 saw sheep numbers (having reached more than 100 million in the early 1890s) reduced by half, a decline in cattle numbers of more than 40%, and an average wheat yield of just 2.4 bushels per acre (0.16 tonne per hectare) [2].

21.3.3.2 Drought Management

The discovery of the Great Artesian Basin (GAB) in 1878 and the drilling of the first GAB bores in central Queensland in 1886–1887, yielding significant volumes of free-flowing freshwater, increased water security and facilitated the settlement of inland eastern Australia. Underlying 23% of the continent (Figure 21.1),

FIGURE 21.1 The extent of the Great Artesian Basin in Australia.

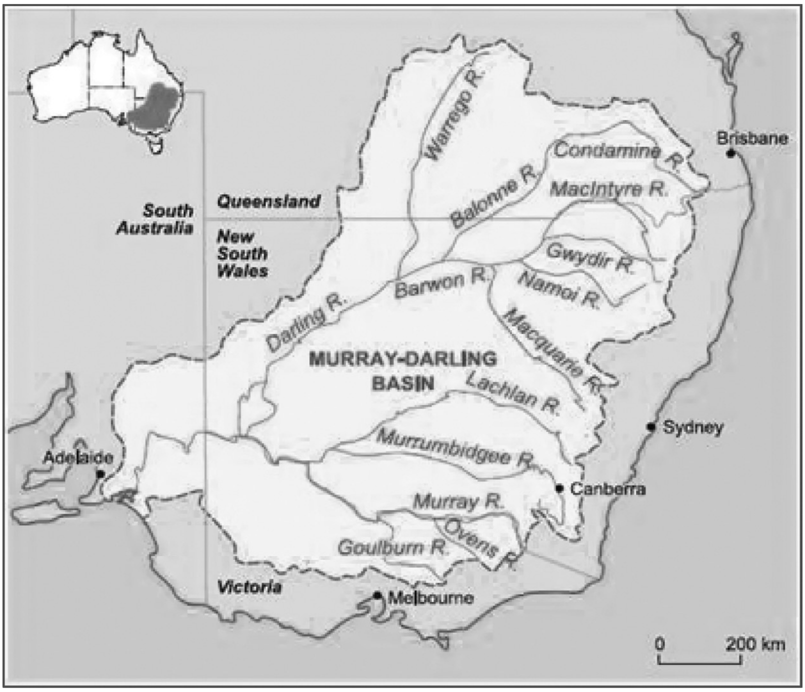

FIGURE 21.2 The extent of the Murray–Darling Basin in Australia.

the GAB is estimated to contain 65 million ML of groundwater [49]. Springs associated with the GAB had supported aboriginal populations for many thousands of years prior to European settlement; early bores drilled into the confined GAB aquifer delivered volumes of around 700,000 L per bore per day, news of which drove a massive expansion of pastoral enterprises across the region. By 1900, 524 bores had been sunk across a vast area of inland Australia and, by 1915, total flow peaked at around 3000 ML a day. Thereafter, declining flows associated with falling water pressure rather than aquifer dewatering rendered numbers of sub-artesian bores requiring pumping to access water. Increasing concern about continuity of access led to the first of many interstate GAB conferences and calls for state governments to control bore drilling. In response, the Queensland and NSW governments assumed ownership of GAB water in 1910 and 1912, respectively, requiring landholders to obtain bore licences and regulating the drilling of new bores [49].

With the establishment of irrigated agriculture along the River Murray in the 1880s and on the Murrumbidgee River in the first quarter of the twentieth century [41], river regulation subsequently also became a focus of water resource management. This was particularly the case in Australia's major river basin, the Murray–Darling Basin (MDB) (Figure 21.2), which covers some 14% of southeastern Australia (approximately, 1 million km^2, roughly twice the size of Spain). Negotiations between the states around water access in the MDB, which was increasingly contested, were a significant focus of the period and led to the signing of the River Murray Waters Agreement in 1914. This agreement had three key objectives designed to ensure continued navigability of the river system, while allowing the development of irrigation; it included arrangements between the states for: joint funding of water storage and river regulation infrastructure; water sharing; and the establishment of a commission to oversee, coordinate, and manage the system according to the agreed rules [37].

21.3.4 Post–World War II Australia

World War II had a detrimental effect on Australian agriculture, with labor shortages, restrictions on the use of superphosphate fertilizers, and isolation from world markets. However, following the war, rapid mechanization, improved technologies, and increased access to supplies contributed to rapid agricultural intensification and increased productivity. In the 20 years after the end of World War II, Australia also ran a large immigration program that saw more than two million people, many of them displaced Europeans, settle in Australia. A major government-assisted infrastructure program at the time, employing some 100,000 people from over 30 countries, was the Snowy Mountains Scheme, a hydroelectricity and irrigation complex consisting of 16 major dams, 7 power stations, and 225 km of tunnels, pipelines, and aqueducts. The Scheme collects water from snow and rain falling in the Snowy Mountains in southeastern Australia, diverting it from the east-flowing Snowy River through tunnels in the mountains to storage dams at the head of the westward-flowing Murray and Murrumbidgee rivers. In addition to generating energy, the Scheme provides vital surface water resources to farming in inland New South Wales and Victoria and has played a significant role in addressing regional water shortages and underpinning economic prosperity, both regionally and nationally. Completed in 1974, the system's construction can be seen as a turning point in Australia's history and symbolic of Australia's identity as an independent, multicultural, and resourceful country [60].

The MDB, then as now, continued to drive Australia's water resource policy due to its importance nationally. (Although only 2% of the MDB is irrigated, it currently produces 70% of the value of Australia's irrigated agricultural output [37] and accounts for 40% of the value of Australia's total agricultural output [64].) Through the middle decades of the twentieth century, political pressure led to increased construction of reservoirs and by 1979 the area irrigated in the MDB had expanded to 1.6 million hectares [41]. However, agricultural intensification in Australia, as elsewhere, has not come without cost. During the 1960s and 1970s, the long-term effects of stocking rates and cultivation practices on land degradation were recognized, became a topic of much public debate, and have since driven both a significant grassroots land care ethic as well as increasing government regulation to ensure sustainable land and resource management. The adoption of new technologies and management practices became and remains increasingly important as farmers try to maintain levels of profitability in the face of rising costs, worsening terms of trade, and restrictions on land use and farming practices.

21.3.4.1 Drought Experience

While Australian farmers have enjoyed significant periods of economic prosperity, they have also experienced times of extreme hardship, brought about by volatile market forces and an unreliable climate, with drought remaining a constant risk. From 1958 until 1968, the most severe drought since 1903 saw crops and pastures fail, and again significant reductions in sheep and cattle numbers as well as declining water storages and restrictions on access to water for irrigation. The drought resulted in a sharp fall in wheat supplies, necessitating wheat imports to meet local demand for only the second time since 1902. However, despite these harsh conditions, economic losses were less severe than expected, possibly due to the reduced pressure on grazing country with more effective rabbit control and the improved transport systems facilitating the purchase and transport of fodder to the areas of greatest need and the movement of stock to less-affected areas for agistment [2].

More recently, the Big Dry in the first decade of the twenty-first century saw water storages throughout southern Australia fall to record low levels. Severe short-term rainfall deficiencies in late 1997, 2002, 2006, and 2008 were exacerbated by a lack of intervening wet years [52] and the prolonged drought affected water availability, agriculture, and ecosystem functioning throughout a large portion of southeastern Australia, a region that supports not only significant agricultural production but approximately 60% of Australia's population [64]. While the economic and social impact of the drought was greatest in the sparsely populated rural areas of Australia, urban water usage was restricted in virtually every state capital city (except Hobart and Darwin) in 2005–2006, significantly raising the national profile of drought.

21.3.4.2 Managing for Drought and Water Scarcity

Issues relating to freshwater supply have been an important topic for political discussion throughout Australia's postcolonial history and, while technological advances and improved practices have contributed to increasing water use efficiency across domestic, urban, and agricultural contexts, the development of effective policy around managing water scarcity and drought risk has perhaps been the most significant advance in recent decades. With its long history of learning to deal with drought and increasing recognition that recurring drought is a natural part of the Australian climate, Australia has been one of only a few countries to have legislated a national drought policy aimed at managing drought risk [16].

21.3.5 National Drought Policy

Until 1989, drought relief to farmers was provided through natural disaster relief arrangements similar to those for floods, bushfires, and cyclones [18,123]. However, drought differs from these more stochastic events, being cumulative in its impact and often without readily definable spatial or temporal boundaries. In 1989, the view of drought shifted to accommodate this difference; drought was acknowledged as a normal part of the Australian climate and subsequently removed from the list of events covered under natural disaster relief arrangements [17].

Following this, a national drought policy was developed, informed by the work of a Drought Policy Review Task Force (DPRTF [46]), and agreed to by state and federal governments in 1992 [17]. This groundbreaking policy was based on the principle that drought was one risk of many (e.g., commodity price risk, exchange rate risk, interest rate risk) facing farm businesses in Australia. The 1992 National Drought Policy focused on drought preparedness and risk management with the core objectives of self-reliance and sustainability [17] but made provisions for events that were rare and severe and considered by government to be "exceptional circumstances" outside the scope of normal risk management [107]. In such instances, business and welfare support was provided in order to keep viable farmers on the land [1]. The package provided certainty around what support would be available in the event of significant drought and avoided the risk of ad hoc policymaking [17].

While it was recognized internationally as world's best practice [17], the 1992 policy was not perfect and over the years has often been revisited and revised. Overall, however, reviews of the policy indicate that its intent remains valid despite difficulties in its implementation, particularly under a changing climate [1]. Consensus has been that the role of government is critical to encouraging effective management of agricultural climate risk through continued public sector investment in agro-meteorological research, development, and extension (RD&E) and supporting viable farmers during the worst droughts [1]. The most recent drought policy review in 2008 had several elements, including assessments of the effectiveness and efficiency of existing drought measures; the social impact of drought; and the likely severity and frequency of future droughts under predicted climate change [17]. It found that

- A majority of farmers across drought-declared regions in Australia were sufficiently self-reliant to manage climate variability.
- Some elements of the policy failed to adequately encourage the adoption of effective long-term drought risk management strategies.
- There are significant challenges in distinguishing between normal and exceptional climate variation, particularly with changes in the global climate.
- A flexible approach is required to determine when government intervention is needed and which aspects of the policy are relevant, given the inherent variability in agricultural production systems and the temporal and spatial unpredictability of droughts.
- The information needs of producers and governments change with changing circumstances [1].

However, despite its intent and these findings, the review (undertaken during the severe and widespread Big Dry/Millennium Drought) and the subsequent Intergovernmental Agreement on drought between federal and state governments at the time resulted in the dismantling of some programs, the announcement of a farm finance package reminiscent of the 1930s, and commitment to a farm welfare program [17]. With worsening drought in eastern Australia, the government returned to the language of natural disaster and crisis management, implicitly rejecting the policy premise that drought is a foreseeable aspect of farm planning [17]. Under growing pressure for assistance, the agriculture minister has pushed for a generous relief package to meet the immediate needs of drought-stricken farmers and their families, many of whom have suffered an extended sequence of extremely variable and, at times, harsh climatic conditions. With worsening drought and stressed farmers, politicians are under pressure to respond—an environment that does not lend itself to sound policymaking [17].

Drought policy advisor and researcher, Botterill, has expressed concern that, in the absence of a considered drought policy package, governments run the risk of ad hoc policymaking that ultimately fails the best interests of farmers, their communities, and the sector as a whole. The 1992 National Drought Policy sought to avoid this by putting in place a stable package of measures that would be ready to access when drought inevitably arrived. Botterill advocates the need for policymakers to revisit the 1990 Drought Policy Review Task Force Report [46] that informed the development of the original 1992 National Drought Policy and to substantially rethink current drought policy settings and design policy instruments (e.g., income-contingent loans) to better support risk-based management aimed at increasing capacity/resilience to cope with severe and prolonged water shortages [17]. The recent federal government "white paper" [34] harks back to the 1992 National Drought Policy and a drought risk management approach, calling for renewed policy focus on drought preparedness and mitigation measures designed to increase the self-reliance of pastoralists and reduce reliance on government for drought relief while still providing in-drought support for farming families experiencing financial hardship. However, the practicalities of delivering on this are still challenging.

As it stands, the Australian national drought policy provides an important social safety net for farmers and rural communities in situations where drought results in economic hardship and declining levels of well-being [16]. However, despite being arguably at the forefront of drought policy development globally, Australia has yet to develop a robust process for monitoring and reporting on drought such as that conducted in the United States through its National Drought Mitigation Center and the National Integrated Drought Information System [16]. Questions also need to be asked about the wisdom of drought policy that considers impacts on only the agricultural sector [31], as well as the relevance of drought policy predicated on historical drought conditions and impacts [16]. Evidence points to the need to ensure greater adaptive capacity across all sectors of society, greater integration of policy areas, and effective mitigation of the drivers of both climate change and water scarcity.

21.3.6 National Water Resource Policy

Among other policy areas, water resource policy also plays an important role in both responding to and building resilience to drought. Australia's major cropping regions are in landscapes prone to highly variable levels of precipitation and water availability and, while highly productive and profitable agricultural intensification in these areas has been driven by supplemental irrigation, there is significant competition for scarce water resources between urban, rural, and natural systems in some regions. State and national water resource management legislation, overseen by the Council of Australian Governments (COAG), aims to ensure equity in the distribution of water resources as well as the sustainability of both surface and groundwater systems. However, the process of evidence-based policy development in this space is often at the mercy of the politics of the day. For example, efforts to provide environmental allocations ("water for the environment") to support natural processes in riverine, wetland, riparian, and floodplain ecosystems, which for years have been shortchanged by the legislation, have been the subject of much social and political debate [16].

Commonwealth, state and local government water policies and adaptation strategies have been repeatedly developed, reviewed, and revised in attempts to better manage the impact of drought and increasing water scarcity, with new interest in preparing for a future with less water [35,37,76]. Currently, the Australian Government's national framework, 'Water for the Future'—a $12.9 billion investment over a ten year period (2010–2020)—aims to secure water supplies through improved water management, including support for healthy rivers, under a range of water policy reforms in rural and urban areas [45,94]. Likewise, water trading provides a viable option for managing drought risk and periods of water scarcity [76,96].

Water trading has existed in various forms in the MDB since the late 1980s, with subsequent revision driven by exceptional drought conditions in recent decades, during which conditions were beyond those planned for when the original water trading rules were developed [96]. Water markets are based on the premise that trading results in the reallocation of scarce water resources to higher-value uses, thereby providing economic benefit to buyers, sellers, and, more broadly, society as a whole [74,96,128]. For example, Peterson et al. [104] estimated that water trading increased the gross regional product (GRP) of the southern MDB by about AU$550 million in a dry year, compared to wet year gains of about AU$200 million. While there are also potential negative outcomes for local communities (e.g., reduced irrigation may result in declining populations and local services [76]) and overall water use efficiency [75], water trading provides an extremely valuable option for irrigators to respond to water scarcity, to reduce the impact of drought on farm production, and to manage debt and risk with changing circumstances through the purchase of additional water for crops or sale of water to earn interim income [76,84,114].

21.4 Current Drought Management in Australia

Both rural and, to a lesser extent, urban communities in Australia have had to learn to adapt to a high level of year-to-year climate variability, to the extent that drought and associated water scarcity are somewhat regular and predictable events. Despite this, significant challenges remain.

21.4.1 Drought Management in Livestock Production Systems

Australia's livestock industries are predominantly pastoral, based on native and "improved" grasslands. They cover some 70% of Australia, generally in drier (semiarid and arid) regions with large diurnal temperature variations and high interannual rainfall variability (Figure 21.3). Climate variability, particularly drought, is a major risk factor in the performance of grazing systems, causing substantial economic and social pressures and in some cases deterioration of the resource base, prolonging recovery when conditions improve [33,89].

21.4.1.1 Challenges

Extreme drought events are a major challenge to the financial, environmental, and social sustainability of individuals, businesses, and communities in rural regions. The economic, social, and resource impacts of events such as the current (2015) Queensland drought (with 80% of the state drought-declared and some pastoralists now in their third year of drought) are devastating for rural communities. In terms of its social impact, drought is an important factor in divorce, suicide, and illness [93] and the extent of distress in drought-affected communities in rural Australia is an issue of deep concern [73]. Historically, government response to drought included providing financial assistance to support pastoralists, with little attention paid to preparedness, early warning, or national alerts when seasonal conditions are favorable. Farm decisions made under stress, in the absence of prior thought and planning, often lead to crisis management and poor decision-making. Unfortunately, the current crisis management approach of governments, while providing support to drought-affected farming families in the short term, is unlikely to be effective in reducing the risk associated with the next drought, with recipients of drought assistance not

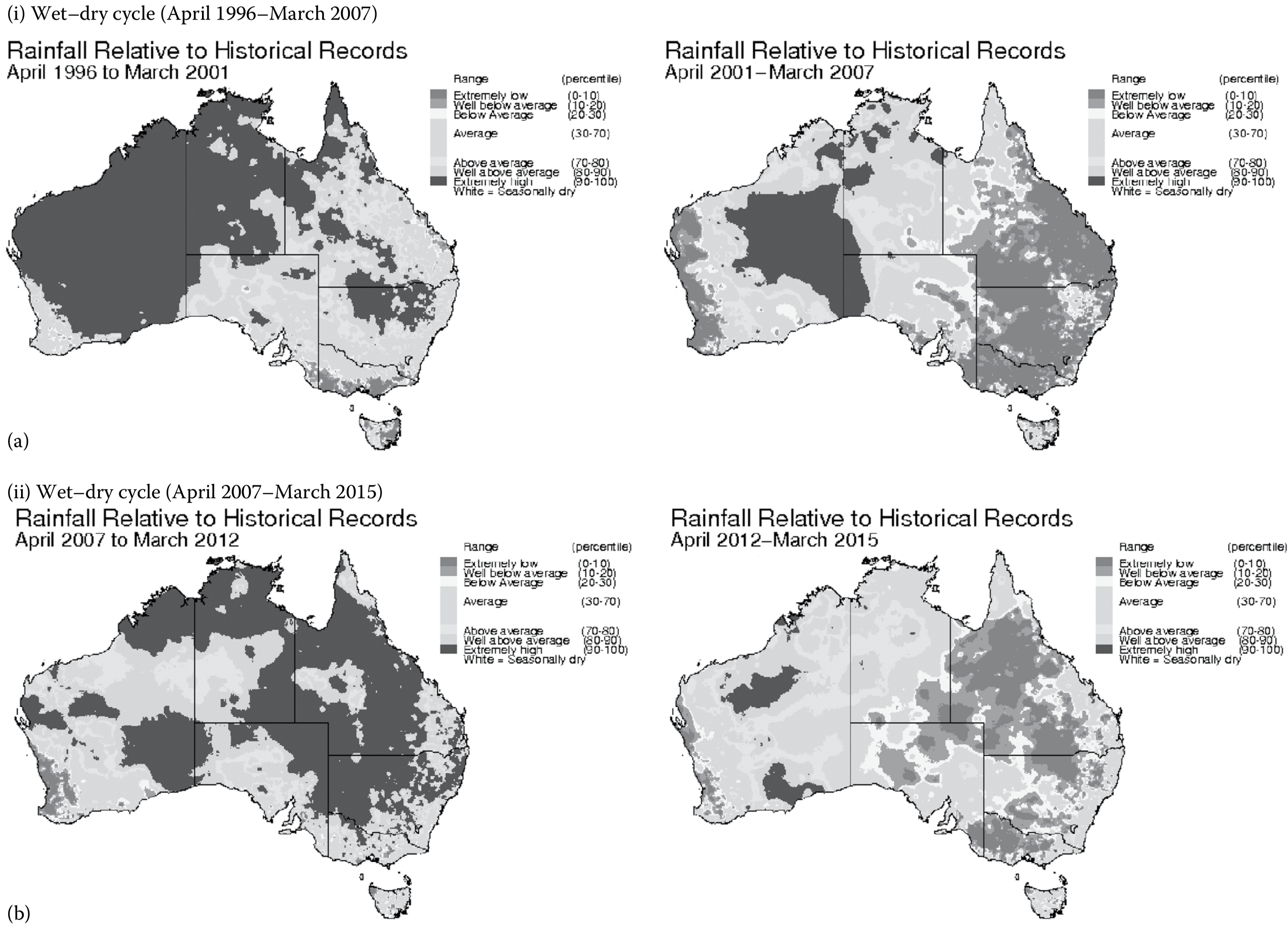

FIGURE 21.3 Australian rainfall relative to historical records showing two wet and dry cycles of approximately 9–13 years over the last 20 years (1996–2015): (a) April 1996–March 2007 and (b) April 2007–March 2015. (From The State of Queensland (Department of Science, Information Technology and Innovation), Brisbane Qld Australia.)

expected to change behaviour or enterprise management practices as a condition of the relief package. Reliance on government relief is contrary to encouraging self-reliance by producers investing in their own "drought-proofing" strategies.

21.4.1.2 Solutions

Initiatives outlined in the recent federal government "white paper" [34] support drought preparedness for pastoralists and include accelerated depreciation for new water and fodder infrastructure (e.g., hay sheds) and improving climate information. Providing incentives to pastoralists for fodder infrastructure, while potentially useful in and near regions where crops are produced, are mostly impractical and uneconomic on the large, extensive grazing properties that exist across vast areas in Australia and in many cases would provide little more than survival feed for a small proportion of the normal herd/flock. On the other hand, improved accuracy of seasonal climate forecasts, longer lead times, forecasts over multiple years, and customized seasonal forecast systems are critical components of a climate service that could provide targeted regional and industry-specific climate information and decision support tools. Drought preparation is vital in favorable seasons, through securing off-farm investments, future provisioning using income equalization techniques, and undertaking proactive property development to improve future drought resilience. To facilitate this, a program of capacity building in planning and readiness for drought is needed during favorable conditions, while during drought producers need to be prepared to make the best decisions when the drought breaks. Further challenges include government-supported monitoring of key drought indicators, early warning systems, national drought alerts or incentives to pastoralists for including drought in property planning, and using sustainable stocking rate practices (e.g., low utilization of pasture or safe carrying capacity) that could reduce future impacts and lessen the need for government intervention in the future.

Climate forecasts may be used to increase the chance of success or contribute to greater confidence in adopting new approaches to drought management, but their application in Australian pastoralism depends on many things including location, enterprise (beef, sheep, wool), and the nature of the management cycle [71]. There are many decisions that can be changed based on a climate forecast but matching the timescale of decision with that of the forecast is important. Decision-making will be facilitated by improved access to regionally downscaled short-term weather forecasts, seasonal forecasts, and multiyear assessments.

Along with rainfall, stocking rate is an important driver of animal productivity in the pastoral zone and because of this, making adjustments to stocking rate (e.g., buying, selling, agistment) is a common means of using seasonal forecasts in drought management [71]. A number of tools have been developed by government agencies to assist on-farm decision-making in the Australian pastoral industry. These include AussieGRASS [26], a decision support tool developed in the early 1990s to monitor key biophysical processes associated with pasture growth, degradation, and recovery and provide early warning of imbalances between livestock numbers and forage supply and a series of financial and long- and short-term stock management tools to aid decision-making before, during, and after the drought [32,120].

21.4.2 Drought Management in Crop Production Systems

21.4.2.1 Challenges

While drought may be most noticeable or visible on animal production systems through its impacts on animal, landscape and pasture condition, drought (either as a meteorological or as a hydrological event) can also impact in a significant way on crop production and yield [106]. Climate variability leading to water deficit stresses can cause severe reductions in crop growth, development, and survival, depending on the severity of the stress, the growth stage at which the stress occurs, and the genotype [80,112,134]. For example, the impacts of drought on crop yield may differ greatly for maize, cotton, wheat, soybeans, and sorghum because they are planted at different times during the growing season, have different water requirements, and different sensitivities at various growth stages to both water and temperature stress [11].

Despite these differences, the impact of major drought in the Australian context on both summer and winter cropping systems is especially evident when considering total national yields and gross value of production. For an example, as the development of on-farm and off-farm infrastructure such as irrigation schemes processing mills and shipping facilities has continued to mature, the gross value of cotton produced in Australia has generally increased since 1985; however, there are clear exceptions this during ENSO drought years including 1986/1987, 2002/2003, 2003/2004, 2006/2007, 2007/2008, and 2014/2015 [90,102,130,134].

Post–World War II, both the production and area planted to wheat in Australia have generally trended upward from 1.4 million tonnes grown on 3.4 million hectares in 1945 to 27.4 million tonnes grown on 13.5 million hectares in 2011 [4]. Again, despite advances in cropping technology, major exceptions are evident in the ENSO drought years of 1944/1945, 1957/1958, 1965/1966, 1967/1968, 1972/1973, 1977/1978, 1982/1983, 1987/1988, 1992/1993, 1994/1995, 2002/2003, and 2006/2007 [4]. During the 2007 ENSO drought, 10.8 million tonnes of wheat were grown on 11.7 million hectares. This is in comparison to 27.4 million tonnes on 13.5 million hectares during the 2011 La Niña event.

Australia's cropping zones include regions with the highest naturally occurring annual rainfall variability in the world [82,123]. This variability is a major driver of production and has important impacts on farmers' incomes, regional communities, and the Australian economy overall [6,105]. For example, the 2002 El Niño event and associated drought not only impacted on crop yields but also reduced Australia's gross domestic product (GDP) by 0.75% [103].

While some crops such as cotton have a certain ability to compensate for changes in growing conditions (soil moisture, temperature) due to their indeterminate growth pattern, it is generally considered difficult to make major changes in the management of any crop after planting [134]. Symptoms of drought stress in crops can range from patchy germination and/or discolored and stressed young plants to older leaf yellowing (wheat, barley) or reddening (oats), followed by death. In other crops such as lupins and chickpea, flowers are aborted, pod set is significantly reduced, and plants are stunted. Drought can also induce deficiencies of soil-immobile nutrients that become unavailable to the plant when the topsoil is excessively dry. While such deficiencies would usually disappear after sufficient rainfall has occurred to replenish soil water profiles, there are no readily available management responses to address these issues (even the application of nutrients to stressed crops has minimal or no effect). Other challenges related to drought management in Australian cropping systems include maintaining profitability and sustainability, while dealing with potential soil degradation and erosion from lack of ground cover [76]. Therefore, any planned responses to expected drought-related stresses need to be made prior to planting.

21.4.2.2 Solutions

In order to manage the high variability of Australia's climate, options focused on improving resilience, sustainability, and profitability have been developed at a farm, industry, and policy level. The majority of these options can be considered as encouraging best management practice as they are focused on climate risk management and soil and crop management [14,67,90]. Whether these options have been developed in response to the need to manage climate risks or the need to ensure ongoing economic viability is a moot point, so long as suitable and practicable options are developed to suit the particular cropping system [90,127,134].

21.4.2.2.1 Climate Risk Management

As discussed earlier, climate variability across Australia's cropping regions is largely driven by large-scale climate phenomena such as ENSO [106]. Increased knowledge of and management of this variability through the use of historical climate data, weather and seasonal climate forecasts, such as those based on the SOI [124], have the potential to minimize risk and allow growers make more informed decisions. By integrating this climate risk information with production system analysis and data such as historic crop yields, growers increase their ability to mitigate the likely impacts of climate variability.

Although the level of uptake and use of climate risk information varies between regions and industries, there remains a continual demand for integrated climate risk management information. Bange et al. [14] in a review of potential adaption strategies for the Australian cotton industry, identified as a priority the need to support the further development of climate risk decision support tools, appropriate extension, and industry engagement and research into alternative management options. This priority is by no means restricted to Australian farmers. Traore et al. [127] also identified a demand by African cotton growers for climate information and highlighted the need for effective science and extension services to assist agricultural communities manage climate risks.

21.4.2.2.2 Soil and Crop Management

Since the ENSO droughts of the early 1990s, there has been an increased focus on the development of crop management practices across Australia that minimize production risks [14,67,77]. Many of these practices are focused on maximizing moisture conservation and include, for example, maintaining stubble cover particularly when undertaken with zero or minimum tillage practices, developing farm rotation systems that include long fallows to increase soil moisture profiles for irrigated crops such as cotton, matching the area to be sown with the amount of available irrigation preseason, and maximizing crop water use efficiency through nutrient management (e.g., tailored use of nitrogen-based fertilizers, incorporating leguminous crops into a rotation system).

Other options to manage drought risk may include monitoring environmental conditions such as subsoil moisture profiles, seasonal climate risk assessments, and market indicators to enable more informed decisions about: crop substitution (e.g., wheat or chickpeas); timing of planting (e.g., planting grain sorghum later during an El Nino event to avoid early spring heat and increase the chance of receiving in-crop rainfall); changing planting configurations (e.g., solid set to skip row or wider row spacing) to stabilize potential yields in likely poor growing seasons); irrigation scheduling; and managing pest, diseases and weeds, many of which respond strongly to climate variability and can further stress drought affected plants and deplete soil water profiles.

At an industry and government level, significant support has been directed toward plant breeding and molecular genetics programs to develop more drought- and heat-tolerant crop cultivars and varieties, as well as the development of tools and training to facilitate access to and skills in interpreting climate data and assessing alternative management options. Many of these tools have taken the form of discussion-support systems. These rely on process-based crop growth models, which can be routinely used to assess the relationship between climate impacts on crop growth and yield, soil moisture profiles, potential management responses, and financial profitability. Whopper Cropper, for example, is a database of prerun APSIM [72] crop simulations incorporating varying management options and is designed to give users the crop modeling power embodied in APSIM without the complexity of calibrating or running APSIM itself [36]. Such systems further help in taking greater advantage of seasonal climate forecasts for planning farm activities [36,91].

As there is no one solution to managing climate variability and drought for an industry as diverse as the Australian grains and cropping industry, the best adaptation strategy is to develop more resilient production systems. Through the early adoption of best practice and monitoring environmental conditions and risks, growers increase their ability to respond to challenges as they arise.

21.4.3 Drought Management in Urban Environments

Some 85% of Australia's population of 23.6 million [5] live within 50 km of the coast. As a result, Australia's major cities, with some notable exceptions (e.g., Adelaide, Perth), generally experience limited exposure to water scarcity and, overall, a relatively low level of drought risk. Despite this, water shortages do occur during the most severe droughts and municipalities are increasingly aware of the need to promote water use efficiency through a range of mechanisms.

21.4.3.1 Challenges

The creeping cumulative nature of drought has often found state and local governments wanting in terms of planning for such events. Even as recently as the Big Dry/Millennium Drought at the turn of the twenty-first century, reportedly the worst experienced since European settlement [52], difficult decisions were put off until the last moment. State governments were still arguing over water rights, and local communities over water recycling, when water levels in many of Australia's largest dams were down to 15%.

21.4.3.2 Solutions

Despite this, once government and the public decided to act, this happened quickly through a series of coordinated measures. Strict limits on water consumption were introduced and enforced with heavy penalties for non-compliance. Bans were placed on the use of garden hoses, washing cars, watering gardens, and filling swimming pools, and it became compulsory to install rainwater tanks and water-efficient shower heads. Water prices were significantly increased in most major cities to better reflect the scarcity and value of the resource (e.g., Grafton and Kompas [58]). The Australian government also made commitments to invest over AU$50 billion on water improvement measures over the next 10 years with major projects such as the building of desalination plants and new pipeline infrastructure. In 2006, Perth became the first Australian city to operate a reverse osmosis seawater desalination plant, which now supplies 17% of Perth's drinking water supply. Desalination plants have also been built in Sydney, Melbourne, Adelaide, and the Gold Coast. Other water improvement projects being funded by government include a comprehensive water accounting program, better water metering in homes, construction of massive new water pipelines, and improvements to farm irrigation systems.

The lessons from this experience have been significant. Despite past experience and scientific evidence of drought risk, political wrangling and inaction, as well as gross mismanagement of water resources, when catastrophe was imminent, both the government and public found the collective will to act. The response was unprecedented in both nature and scale, involving cooperation across state and federal governments; root and branch reform of water management and planning; introduction of strict limits on the use and consumption of water; increased water prices and the introduction of water trading; and massive public investment in new infrastructure. This response was backed up by powerful public awareness and education campaigns that changed public attitudes toward drought and made it socially unacceptable to waste water. Increasing community awareness of the impact of drought and the real value of water contributed to a fall in household water consumption throughout Australia, reversing a predrought nationwide trend of increasing water consumption of 8% per capita between 1993 and 2001 [44].

The results show that substantial reductions in the use of an essential resource are achievable–in a short time and at relatively low cost–where regulatory and market responses are underpinned by social awareness and support. Significant price increases (40%–70%) may be acceptable to the public where the reason for the increase is understood and the additional cost represents a relatively small proportion of the household's total expenditure. However, responses were not always the most cost-effective, ranging from AU$770 to AU$33,395 per ML of water saved [38], and the water consumption targets introduced were not always met. Once the drought ended, average daily water use started to increase again [110] and, while water prices have remained higher than they were pre-drought, Australians still spend less on water than they spend on any other essential services such as electricity [3]. Each year, water companies also lose large quantities of water due to leaking pipes and overflows; during the drought, water losses in Brisbane, Sydney, and Melbourne in 2007 were between 76 and 107 L per connection per day [95]. Several years on, many of the planned infrastructure projects are delayed, behind schedule, or over-budget.

21.5 Future Drought Risk in Australia

Climate change is aggravating drought risk through changes in rainfall patterns and increasing heat and evaporation [113,121,140]. Climate models predict that Australia is likely to experience greater frequency and intensity of droughts and heat waves; in particular, drought frequency is expected to increase in southwest and southeast Australia, with rainfall declining by as much as 10% by 2030 and up to 30% by 2070 [113,121]. In Australia, where percentage changes in mean annual precipitation are generally amplified by as much as two to three times in mean annual streamflow [28], projected increase in the duration and intensity of droughts will exacerbate water scarcity conditions [39,121]. For example, integration of hydrological models with future climate projections suggests that, under a 2°C warming scenario, freshwater resources in southeast and southwest Australia will decline 0%–40% and 20%–70%, respectively, due to a reduction in winter precipitation [113].

If realized, predicted increased drought risk will have far-reaching effects on agriculture in Australia, significantly impacting Australia's most important agricultural regions, including the largest catchment and most productive agricultural area in the country, the MDB, and the southwest wheat belt [69]. The economic impact of droughts on local industry and the national economy can be substantial. The widespread Big Dry/Millennium Drought (1997–2009) resulted in 6% decrease in the GDP of one of Australia's key agricultural regions, the MDB (0.75% of national GDP), along with the temporary loss of 6000 jobs [137].

21.6 Summary and Conclusions

In the past, incremental adaptation was often sufficient to manage drought risks, but an increasing frequency of droughts and reduced rainfall will potentially drive the requirement for transformational change. Future drought risk management will depend on good planning, not only during adverse seasons but also in more benign times, recognizing that making the most of good seasons is a key component of managing drought risk and improving drought preparedness.

Authors

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22

Politics of Drought Management and Water Control in India

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Abstract The unequal impact of drought is increasingly evidenced in the drought-prone areas of Maharashtra state, India. Ongoing relief programs have neglected water scarcity and the control of water by the economically powerful sugar mills and farmers. Mitigation projects are all implemented with the intention of avoiding harm to the economic interests of those who control the water. Sustainable water resource management in this drought-prone area has become an insignificant policy issue, furthering the resource crisis of the state and challenging the concept of ecological sustainability.

22.1 Introduction

Drought is in fact one of the oldest known disasters in India; however, the government still does not fully accept the level of disaster that drought represents [7]. This chapter discusses drought and government initiatives in western Maharashtra and its efforts to tackle drought risk in one of most backward drought-affected areas of India known as Vidarbha region of the western Maharashtra state. The Vidarbha region is also notorious for its instances of farmer suicide. A special package for farmers was introduced after widespread suicide, but it did not stop farmer suicide in the region. In spite of the large amount of money—Rs 37,500 million—927 farmers committed suicide in 2012. This chapter does not discuss this issue in detail. The issue of flow control for deterring flood is also beyond of this chapter's scope [6,16]. Rather, the continued drought in the western Maharashtra and the lack of willingness of the state to regulate water use there is our focus.

In addition, we look at the political economy of water regulation and supply in this drought-prone region. Media reports and field work in three villages there are analyzed to study the water control issue.

The main argument of the chapter is that drought mitigation in the state is furthering economic inequality and creating de facto water regulators. Mitigation of the environmental effects of water control is completely neglected due to the influence of these parties.

22.2 Theoretical Framework

Drought mitigation is a politically determined process in India. This is primarily due to the importance of the state in regulating and controlling water resources. Governmentality is the deciding factor. "Governmentality" is defined by philosopher and social theorist Michel Foucault as the art of governing and the exercise of power to reinforce, strengthen, and protect the principality (power center) [5]. It also concerns the manipulation of relations of forces that would permit the power center to ensure its existence/protection, and it explains how the ability to possess power is different from that of governing the process, which protects the interests of the ruling power. The term "ruling class" is not used; but, the ruling class' existence is given prime importance in the present-day political order. Foucault further explained: "state is no more than a composite reality and a mythicized abstraction, whose importance is a lot more limited than many of us think. Maybe what is really important for our modernity—that is, for our present—is not so much the nationalization of society, as the 'governmentalisation' of the state" [5].

Governmentalization is a must in a welfare state regime, where every subject expects government involvement in the distribution of resources [8]. Infact governmentality is quite visible in the form of interventions and the process of governance [4]. The post-modern state (contemporary) is incapable or neglects to understand the specificities of its subject, such as their wealth, their land holdings and yields, their location, and their very identity [13]. This contemporary reality is reflected in natural resource management. Those who control the government also own the natural resources. There are arguments that the conflict between biopolitics (and the impulse to improve a population as a whole) and neoliberal forms of governmentality (with their injunctions in favor of prudence and self-reliance) is increasingly reflected in contemporary development governance [2].

Governing water in drought-affected areas is integrated with the principles of contemporary governmentality. The reported severity of water in these places necessitates the importance of a regulating/controlling mechanism of water resources. Water scarcity is a multifaceted issue, and water scarcity must be examined in the context of multiple-level water users [3]. Water availability—and the contributions of human activity and intervention—should be assessed in a broader context. Regulation of water resource is must for drought mitigation, however, it has been proved that economic interest has impinged on water resource regulation. Regulation which affect the profit of capital class undermine all natural method of conservation and mitigation of water for better management of drought. The exclusion of marginal framers and poor masses from the governance of water in drought-affected areas proves the presence of a governing state apparatus while maintaining the hierarchy (interest) of the state. Here, those who assign high economic value are really governing the water by governmentalizing it. Governmentalizing is attached with those interests that protect capital and state interests at the same time.

22.3 Drought in Maharashtra

A famine broke out in the Marathwada region under Nizam of Hyderabad's regime; in 1899–1900, the region was declared a famine zone. The Aurangabad and adjoining districts were exposed to severe famine in 1749 and 1787. In 1871, the district of Aurangabad experienced a severe drought. The history tells the problems of drought especially in the management of water. The western Maharashtra, well known for water scarcity, requires effective water management. The water use pattern of the drought-affected area requires certain specific regulation and control. The drought scenario in this region rejects the development practices of Maharashtra state.

The government of Maharashtra has declared drought in the state, especially in the western region. The severity of drought is suspected to be greater what the state experienced in 1972. The central government

TABLE 22.1 District-Wise List of Identified Drought-Prone Districts in Maharashtra

			As per CWC Study	
State/District	No. of Talukas	Area of District (km²)	No. Talukas Affected by Drought	Area Affected by Drought (km²)
Maharashtra	100	123,767.05	45	57,664.7
Ahmednagar	13	16,762.2	7	9,491.8
Aurangabad	12	16,385	2	3,111.3
Bir	7	11,169	3	4,595
Nasik	13	15,631.5	7	8,098.9
Osmanabad	11	14,027	7	9,515
Pune	14	15,688.2	4	4,932.1
Sangli	8	8,610.25	5	5,939.66
Satara	11	10,436.9	4	3,878.5
Sotapur	11	15,057	6	8,102.5
India	725	1,081,131.38 in 99 districts	315	511,288.64 in 74 districts

Source: Tata Institute of Social Sciences Access, http://www.maharashtrastat.com/default.aspx.

TABLE 22.2 Number of Districts, Blocks and Area Covered under Drought-Prone Areas Program (DPAP) in Maharashtra (2009–2010)

State	Number of Districts	Number of Blocks	Area (Lakh, ha)
Maharashtra	25	149	194.5
India	195	972	745.9

Source: Tata Institute of Social Sciences Access, http://www.maharashtrastat.com/default.aspx.

has already sanctioned Rs 12,070 million for drought mitigation. Tables 22.1 and 22.2 show the severity of the drought in Maharashtra. They also indicate the importance of large-scale intervention.

Rainfall data prepared by the Indian Meteorological Department, by the district divisions of three drought-affected districts—Sholapur, Osmanabad, and Jalna (see Tables 22.3 through 22.5)—indicate the drought crisis in the region.

The state is ready to meet the requirements of drought-affected people, but field workers in some villages in Osmanabad district and media reports show the other side of the issue. The facts are not new to the people who live and experience drought, however, continuation of the crisis is a matter of debate. It was reported that the drought in Marathwada region is man-made: somebody is controlling the water. Media reports say that water from the Ujini Dam in Jalna district (one of the worst affected districts) has been diverted to sugar mills owned by local political leaders. Many reports prove there is a pipe between the sugar factory and the river. The report goes on to describe a large-scale migration from the villages. The local community even begs tanker suppliers for the water meant for the trees and not for drinking. The tanker water supply by the panchayat (local self-government) is the only source of drinking water.

The root cause of the crisis is the shifting agricultural pattern. Sugarcane needs 10%–15% more water than any other crop. Sugarcane cultivation in the rain shadow area itself is disastrous, as there are no systems in place to question the powerful sugar lobbies in the state. The origin of such a powerful group traces back to the early 1960s. Marathas, a particular caste, dominated the politics of the state [12]. This group is estimated to constitute 40% of the population, but they control over 80% of government and political party positions [14]. They dominate the western Maharashtra region, that is, the sugarcane cultivation area. The sugar industry was the largest financial supporter of Maharashtra politics [1]. All the important positions in the cooperative societies, local governments, and other social institutions were held by sugarcane owners, who were responsible for the system's dysfunction [11], creating a situation where all

TABLE 22.3 Sholapur District Rainfall

Year		2007	2008	2009	2010	2011
January	R/F	0	0	0	21.4	0
	%DEP	−100	−100	−100	478	−100
February	R/F				1.4	
	%DEP	−100	−100	−100	−18	−100
March	R/F		49.7			
	%DEP	−100	1208	−74	−100	−100
April	R/F	0.1	7.7	0.8	5.1	27.4
	%DEP	−99	−19	−92	−46	198
May	R/F	0.2	4.8	32.8	3.6	18.9
	%DEP	−99	−82	23	−86	−37
June	R/F	227	27.7	75.3	146.1	39.4
	%DEP	117	−73	−28	40	−62
July	R/F	49.8	63.4	54	182.3	142.6
	%DEP	−52	−39	−48	75	43
August	R/F	143	156.2	167	258.2	174.8
	%DEP	33	45	55	139	72
September	R/F	223.4	279.1	230.4	138.2	43.3
	%DEP	23	53	26	−24	−75
October	R/F	0	58	109.8	86.2	52.9
	%DEP	−100	−30	33	4	−44
November	R/F	9.5	25.4	54.1	36.6	0
	%DEP	−64	−3	106	40	−100
December	R/F	0	0.5	3.2	2.8	0
	%DEP	−100	−92	−48	−55	−100

Notes: (1) District rainfall (mm) (R/F) shown below gives arithmetic averages of rainfall of stations under the district, (2) %DEP are departures of rainfall from long period averages of rainfall for district, (3) Blank spaces show nonavailability of data.

the irrigation facilities were available to the politically stronger sugar farmers in western Maharashtra, and financial support from the government flowed to them. Tables 22.6 through 22.8 show the irrigation details of the state and the importance of sugarcane.

Irrigation facilities in the state attest to the fact that sugarcane farmers are its main beneficiaries. One-hundred percent of sugarcane areas are irrigated; compared to farmers of other crops, sugarcane farmers receive the full benefit of irrigation in the state. Tables 22.9 and 22.10 show the number of sugar mills in the state.

22.4 Crisis of Drought Management

Water is not scarce to everyone; sugar farmers in western Maharashtra are not facing acute water scarcity. The sugar mills are getting adequate water from the rivers and they are exploiting the groundwater. Marginal farmers and poor households in entire regions now depend on a private tanker water supply. These are demonstrated facts; a truth that has nevertheless failed to regulate or challenge the flourishing tanker water industry, which is a flourishing business in the region. Many reports on the growth of water tanker business in the region are available. Sainath analyzed reports in *Loksatha*, a Marathi daily newspaper, on the tanker mafia in the Marathawada region (the Hindu daily dated March 27, 2013). He reported that the water market in Marathwada is flourishing, that the newspaper reports how tanker owners earn Rs 6–7.5 million in water sales every day. *Loksatha* reported that tanker owners buy 10,000 L for

TABLE 22.4 Osmanabad District Rainfall

Year		2007	2008	2009	2010	2011
January	R/F	0	0	0	20.8	0
	%DEP	−100	−100	−100	995	−100
February	R/F				3	8
	%DEP	−100	−100	−100	20	208
March	R/F		46.9	0.4	0	0.1
	%DEP	−100	898	−91	−100	−97
April	R/F	0.2	22.8	2.4	1.1	14.2
	%DEP	−98	178	−71	−87	89
May	R/F	0.7	0	26.5	5.7	11
	%DEP	−98	−100	−10	−81	−58
June	R/F	197	51.2	49.9	151.7	51.9
	%DEP	37	−64	−65	5	−61
July	R/F	67.1	88.5	105.1	351.5	185.8
	%DEP	−60	−48	−38	108	20
August	R/F	129	187.8	230.1	284.6	181.3
	%DEP	−30	2	25	54	18
September	R/F	221.7	355.6	203	163.4	51.5
	%DEP	17	83	6	−16	−72
October	R/F	0	5.8	93.2	59.9	59.5
	%DEP	−100	−92	21	−23	−30
November	R/F	0	10.3	43.4	27.1	0
	%DEP	−100	−55	90	19	−100
December	R/F	0	2.3	7.3	1.3	0
	%DEP	−100	−56	40	−75	−100

Notes: (1) District rainfall (mm) (R/F) shown below gives arithmetic averages of rainfall of stations under the district. (2) %DEP are departures of rainfall from long period averages of rainfall for the district. (3) Blank spaces show nonavailability of data.

Rs 1000 or 1500 and sell at a rate of Rs 3500. The report quotes the ex-member of parliament and ex-MLA (Maharashtra legislative assembly) member. Prasad Tanpure said more than 50,000 medium and big tankers were manufactured in the state that year. It cost roughly Rs 30,000 to make a 10,000 L capacity tank [11].

Life in the local community is interrupted by drought; however, the governance of the state has not been affected. State presence in the drought-affected areas is limited to its arranging deliveries by a private tanker to supply water to villagers. These tankers take water from private ponds, rivers, and wells. The tanker owners pay to collect the water. The drought-affected community does not pay any money, so the entire responsibility is entrusted with the local panchayat (village council). This process is not economically beneficial to the panchayat, but it is a social safety net for the survival of panchayat institutions.

22.4.1 Struggle for a Neglected Life

Apshinge, Katree, and Kamothe are the three most yet neglected villages in the drought-prone district of Maharashtra–Solapur. Drought is not new to villagers there. Water is a scare resource and the scarcity has in fact redesigned local society and individual life. Major water bodies like ponds, rivers, and small streams are already dried up and what remains is slowly vanishing. All the tube wells in the village are defunct, so the entire village depends on tanker water. Tankers come every three days, supplying water on the spot for those who show up. The tanker lorry suppliers hardly calculate the amount of water in the supply. The existing social and economic infrastructure never gives effective

TABLE 22.5 Jalna District Rainfall

Year		2007	2008	2009	2010	2011
	R/F	0	0	0	7.2	0
January	%DEP	–100	–100	–100	–106	–100
	R/F	0	0	0	0	2.3
February	%DEP	–100	–100	–100	–100	15
	R/F	0		0	0	0
March	%DEP	–100		–100	–100	–100
	R/F	0	0	0	0	0.1
April	%DEP	–100	–100	–100	–100	–96
	R/F	0	0	21.4	0.4	1.9
May	%DEP	–100	–100	24	–98	–89
	R/F	79.3	66.9	33.1	97.2	37
June	%DEP	–42	–51	–76	–29	–73
	R/F	147.5	124.8	209.4	288.1	224.4
July	%DEP	–11	–25	26	74	36
	R/F	122	121.8	173.8	304	197.9
August	%DEP	–28	–28	2	79	24
	R/F	136.4	211.9	121.7	117.4	97.8
September	%DEP	–14	33	–23	–26	–31
	R/F	0	0	58.7	33.7	0
October	%DEP	–100	–100	141	38	–100
	R/F	0	0	58.7	33.7	0
November	%DEP	–100	–100	141	38	–100
	R/F	0	0	0.4	0	0
December	%DEP	–100	–100	–94	–100	–100

Notes: (1) District rainfall (mm) (R/F) shown below gives the arithmetic averages of rainfall of stations under the district. (2) %DEP are the departures of rainfall from long period averages of rainfall for the district. (3) Blank spaces show nonavailability of data.

support to farmers for generating alternative livelihoods, so these are limited to the running of a small shop in the front room of one's house*.

22.4.2 A Permanent Struggle

A farmer pays Rs 3000 for 10,000 L of water. Eight farmers in the area obtain water from these sources; they are forced to buy the water because they have no other livelihood. They are forced to migrate to large cities to eke out a living, where they can find employment in factories and construction industries. A field visit shows that a farmer had 30,000 ft^2 of land, which is further divided among six brothers. They are unable to feed the cattle as fodder is becoming costly, and they cannot grow it, as they have no farm. These farmers further describe the absence of an irrigation canal in the area.

22.4.3 Excerpts from Real Life Stories: Drought and Existence

A farmer who used to cultivate onions has given up farming owing to water scarcity. He has his own well, but it has no water in it. The land close to his land is owned by six farmers, who have a cooperative culture and

* Tanker lorry supply water on specific time and if people are not able to collect it from the spot will not get it. Otherwise they have to wait till next lorry comes. Tanker water supply is based on its capacity to carry and not necessarily the need of the people. So it is fully dependent on the tanker's capacity and profit.

TABLE 22.6 District-Wise Land Utilization in Maharashtra (2005–2006) (100 ha)

Districts	Net Sown Area	Gross Sown Area	Net* Irrigated Area	Gross** Irrigated Area	% Gross Irrigated to Gross Sown Area
Thane	2,446	2,506	190	208	8.3
Raigad	1,885	2,155	111	134	6.2
Ratnagiri	2,444	2,558	45	54	2.1
Sidhudurg	1,403	1,590	332	365	23
Nasik	8,846	9,750	2,016	2,420	24.8
Dhule	4,358	4,966	449	538	10.8
Nandurbar	2,966	3,402	518	535	15.7
Jalgaon	8,509	14,515	1,558	1,728	11.9
Ahmednagar	11,187	14,681	3,466	3,791	25.8
Pune	9,408	11,509	2,632	3,129	27.2
Solapur	10,316	11,188	2,517	2,899	25.9
Satara	5,520	6,665	1,636	2,161	32.4
Sangli	6,074	7,222	1,355	1,505	20.8
Kolhapur	4,285	8,233	1,197	1,258	15.3
Aurangabad	6,899	10,682	1,557	1,801	16.9
Jalna	5,713	7,255	739	1,075	14.8
Beed	7,569	9,038	1,977	2,362	26.1
Latur	5,188	7,243	560	611	8.4
Osmanabad	4,785	7,162	1,108	1,362	19
Nanded	7,025	8,194	649	876	10.7
Parbhani	4,855	8,648	441	653	7.6
Hingoli	3,295	5,218	509	719	13.8
Buldhana	6,675	8,369	379	452	5.4
Akola	4,350	5,278	184	256	4.9
Washim	3,780	5,490	217	247	4.5
Amravati	7,519	10,801	782	937	8.7
Yavatmal	8,476	9,762	534	616	6.3
Wardha	3,645	3,866	309	408	10.6
Nagpur	5,473	5,970	1,232	1,472	24.7
Bhandara	1,783	2,195	1,144	1,265	57.6
Gondia	1,829	2,109	980	1,099	52.1
Chandrapur	4,515	5,494	1,050	1,161	21.1
Gadchiroli	1,712	1,844	589	631	34.2
Maharashtra	174,733	225,558	32,962	38,728	17.2

Source: Tata Institute of Social Sciences Access, http://www.maharashtrastat.com/default.aspx.
* The total areas under cultivation.
** Total cultivable area.

share water. The farmer has said he is not taking water from that the cooperative, since they do not want to share water with a lower caste famer (Dalit*). Even though he has 5 acres of land, his main source of income is a cow that gives 3 L of milk a day. His family is living on that income. Since this farmer's region, Thuljapur Block, is not included in the drought-prone area, farmers there get no support from the government.

Apart from small farmers, the nomadic tribes in the villages are most affected. They are also known as an ex-criminal community. They possess no agricultural land. Local self-government supplies tanker water; the people believe the panchayat is collecting the cost of the tanker water from house taxes. They are

* The depressed caste in Indian society.

TABLE 22.7 Gross Cropped/Irrigated Area and Area under Food Grains with Cropping Intensity in Maharashtra (2007–2008) (Area in 1000 ha)

State	Cultivated Area		Cropping Intensity (%)	Irrigated Area		%Net Irrigated Area to Net Cultivated Area	Area under Food Grains	Share of Area under Food Grains to Total Cropped Area (%)
	Net	Gross		Net	Gross			
Maharashtra	17,473	22,655	129.7	3,181	4,433	18.2	13,033	57.5
India	140,861	195,835	139	62,286	87,259	44.2	125,969	64.3

Source: Tata Institute of Social Sciences Access, http://www.maharashtrastat.com/default.aspx.

TABLE 22.8 Percentage of Irrigated Area to Total Area under Principal Crops in Maharashtra—Part II (2007–2008) (in %)

State	Gram	Total Pulses	Total Food Grains	Groundnut	Rapeseed and Mustard	Total Oil Seeds	Sugarcane	Cotton	Tobacco	All Crops
Maharashtra	29.4	10.9	17.5	16.6	—	4.9	100	2.7	14.3	19.6
India	35.3	16.9	47.2	22.7	65	27.1	93.5	35.1	52.6	44.6

Source: Tata Institute of Social Sciences Access, http://www.maharashtrastat.com/default.aspx.

TABLE 22.9 Sector-Wise Number of Operational, Sick, and Closed Sugar Mills in Maharashtra (2011–2012)

	Cooperative Sector			Public Sector/State Owned			Private Sector			Total		
State	Operational	Closed	Sick*	Operational	Closed	Sick**	Operational	Closed	Sick**	Operational	Closed	Sick
Maharashtra	130	38	87	—	—	—	41	4	2	171	42	89
India	251	74	177	19	43	2	261	29	14	531	146	193

Source: Tata Institute of Social Science Access, http://www.mahastate.com.
*The total areas under cultivation.
** Total cultivable area.

TABLE 22.10 Performance of Cooperative Sugar Factories in Maharashtra (2008–2009) (Rs in Lakh)

	Sugar Factories			Paid Up Share Capital*			
State	Installed	Worked	Membership*	Total	Govt.	Sugar Production (in Lakh, Tonne)	Installed Capacity (in Lakh, Tonne)
Maharashtra	165	109	2,451,620	198,698.96	77,512.94	39.92	64.6782
India	317	218	5,527,447	359,014.73	178,660.39	64.18	107.372

Source: Tata Institute of Social Sciences Access, http://www.maharashtrastat.com/default.aspx.
* 2007–2008.

agricultural workers. Drought has affected their agricultural work, so they go begging. They do not have ration cards because the Maharashtra government does not issue these to an ex-criminal tribe. Drought has a different meaning for them: during drought season they must go begging. Since they do not have land, work in agricultural labor is their only source of income, which helps them to get out from under the taboo society places on them. But with little farm work due to continuous drought, the social acceptance derived from their being laborers is greatly impeded.

Life in the Dalit colonies in the village of Apsinge is an extension of caste-based water-discrimination. The colony is in the corner of the village and, in fact, it is separate from other nearby communities. There are 100 families in this *basti* (colony). They are traditionally agricultural workers and they have no farmland. Drought has pushed them from the agricultural land, so they must perform other manual jobs to survive. They have individual water taps but no water supply. They wake up early in the morning, at 3 a.m. to fetch water from an open well.

The farmers who have more acres of land and wealth are overcoming the vulnerability, but small farmers, landless workers and deprived sections are living at the receiving end of the drought.

22.5 A Flow of Money: But Not of Water

The state does not deal with the question of drought; instead, it manages water supply. Unlike previously, drought mitigation now gets additional financial support as part of the Indian government's Disaster Management Act of 2005. The Calamity Relief Fund (CRF) is increasingly being regarded as a panacea for drought mitigation in India. The money allocated for CRF only meets emergency relief expenditures. This is a crisis of governance, also. The Manual for Drought Management states, "The drought management system that has been practiced in India since its independence is largely a continuation of the systems and schemes instituted during the colonial period. It emphasizes a relief-based approach and provides certain other small concessions, which do little to alleviate the distress caused by widespread crop failure" [17]. The colonial administration introduced a famine code to deal with starvation during drought season; post-independence governance scrapped the famine code owing to the administrative reforms for dealing with famine. The major thrust of drought relief is effective water resource management to prevent a severe drought. As the 2009 drought manual explained, "The first step involved in the water resource management process is estimating the demand for water. The district administration can undertake such an exercise on the basis of the consumption needs of the total population of the district and the demand for water from industrial, service and agriculture sectors" [17].

Demand assessment of water is a critical process in the Maharashtra's drought-affected areas, primarily due to the unequal demand pattern. Demands of sugar farmers, sugar mills, and industries are higher than other farmers' demands and the domestic need of the local community. The manual has also elaborated programs such as rainfed area development, mitigation, watershed development, water harvesting, and artificial recharge of groundwater. There is greater demand for better water management. Demand for management is generally confined to the raw water demands of sugarcane factories, and the value placed on the needs of sugarcane farmers is higher than that allotted to other farmers. This economic value is the deciding factor.

Agricultural infrastructure development is also under threat [9]. Canal irrigation projects are not adequately connected to small farms. A dam was constructed in the Jalna district, for example, but no canal has been constructed for transporting the water. Also, the controller and auditor general of India came out with a detailed assessment explaining that delays in the completion of the construction of irrigation projects cost an additional Rs 270,000 million to the government. The report further states that 432,700. One million rupees has been spent for 426 incomplete irrigation projects in Maharashtra. Some projects begun 45 years ago have not yet been completed. These along with corruption in irrigation projects in Marathawada give evidence of the ineffective nature and practices of agricultural infrastructure development in the region. The solution lies in a well-connected water supply network and low extraction of water resources. However, government machinery is actively supplying tanker water, again supporting those who monopolized the water sources.

22.6 Summary and Conclusions

The argument and data of this chapter are not new. Local communities are accustomed to believing a tanker water supply will always be provided. The larger concern here is that year after year, the expectations of small farmers and local communities do not change. The socially accepted solutions are either migrating or depend on the tanker water supply. While the people suffer, the water supply continues to be directed the sugar factories. The state administration experiences no resistance, except for some protests in Mumbai. A general acknowledgement of the crisis depends on the state's admitting it first*.

Political pressure and groups that would raise a local community's concern are disappearing. Mitigation to the farmers benefits the economic class that controls the water resources. What is needed for an agitating mob to spring up is an understanding of how it affects the masses, the society at large. However, the local community appears unable to resist illegal water tapping by the powerful sugarcane lobby. The local farmers who cultivate other crops and the local community have accepted the crisis as a reality; this "collective" acceptance of the crisis has legitimized parallel power structure in the region.

Decades of drought and government responses to drought failed to produce a model of drought mitigation in the Marathwada region. It could have done so, but any mitigation was limited to commodifying water by placing a price on it. Water is thus a scarce resource for the poor and it helps the rich profit from the scarcity. The environment as a whole in the area has been neglected. Scarcity due to environmental negligence again empowers those holding de facto ownership of water resources.

It is incredible to argue that the state is incapable of offering a solution. But it seems no solution is possible without a challenge to the economic interest of the parallel political power. As far the situation is concerned, no mechanism exists for resolving the crisis. The only effective mechanism is to regulate water price, that is, to levy an "optimum market price" for drinking and irrigation water. Only those who are able to afford "the price" of water survive.

The state has a significant political stake to deal with the situation; however, economic governance prefers to deregulate water for the sake of the political existence of the state as a welfare institution. The whole idea of the welfare state is in crisis. Water is a right, but the current political economy of water has seldom considered it a as democratic right. Sustainable water resource governance is losing its institutional form. This is an institutional crisis of the present-day political economy. Governmentalization becomes apolitical and destructive, and this crisis poses a threat to both the theory and practice of governmentality.

Authors

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* People live in backward areas of Mumbai city often fight with municipal authorities and between the tanker water suppliers for drinking water.

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23

Drought Management for Horticultural Crops in India

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Abstract In arid and semiarid regions of India drought is a recurring phenomenon affecting both human and cattle populations on a large scale. Low annual rainfall in these regions coupled with highly erratic and unpredictable patterns are the root cause. Rajasthan, Gujarat, Maharashtra, Telangana, and Karnataka make up the bulk of this region while some stretches are also found in Punjab, Haryana, Madhya Pradesh, and Andhra Pradesh. In these regions farming is unprofitable and unsustainable, and over the years soil fertility has also gone down owing to low biomass production and high cattle pressure on land for vegetation and fodder. In the context of climate change, this situation is expected to get worst unless some drought-proofing mechanisms, technologies, and management practices are implemented.

These include alternate land use systems, namely integrating locally suited perennial fruit trees (horticultural fruit trees) on arable lands with rainy season crops, adoption of rainwater-harvesting structures, application of available limited water for irrigation through advanced methods (*viz.*, drip, trickle, partial root zone drying) and at critical stages or during post-rainy and summer seasons, mulching land between rows of fruit trees with crop residues or legume crops, covering the tree bases with organic or plastic mulch, and adopting sustainable soil management practices to build resilience against drought.

23.1 Introduction

In India, drought knocks on the farmers' door if the south-west monsoon (S-W monsoon; June–September) fails. The available long-term weather data on rainfall indicate that approximately 16% of India's total area is drought-prone on a regular basis and annually about 50 million people in the country are exposed to drought. Another aspect of the monsoon climate which makes most of India's land drought-prone is that 85% of total annual rainfall is received in 3–4 months during the S-W monsoon, exposing vegetation during the remaining 8 months to moisture stress of different intensities. Therefore, crop production is often faced with moisture stress and extreme conditions during drought situations. Fruit tree crops that are perennial in nature do survive the hardest weather compared with seasonal arable crops, but even their productivity is limited by the harsh climates of arid and semiarid regions. Moreover, shifting from arable crops to sole fruit tree crops on a large scale is not advisable as India needs to meet both food grain and fodder demand for its large human and cattle population. Under such situations alternative land use systems, namely agri–horti system, seem to be a strategy that could work better in the long run. Integrating rainy season arable crops (cereals and legumes) with horticulture fruit trees would not only enhance resource use efficiency but also reduce avoidable losses in the system like soil evaporation and soil erosion while improving rainwater-harvesting capacity.

However, the success of a chosen agri–horti system greatly depends on how the drought is managed vis-à-vis land, fruit trees, soil, weed, stored soil moisture, rainwater, and irrigation water management. This chapter covers aspects that would enable farmers to manage drought better and improve their farm productivity even under the hardest climatic conditions. Therefore, the main objective of this chapter is to introduce the readers to the extent and severity of drought in India, its impact on farm output, followed by listing and describing how drought can be effectively managed in the arid and semiarid regions of the country.

23.1.1 Why Do We Talk about Drought in India?

Drought suggests large temporal variations in rainfall pattern. Long-term weather data also suggest that, on average, 4 out of 10 years witness highly erratic rainfall, resulting in drought of varying degrees over two-thirds of the total sown arable land. In India, most of this drought-prone area (35% of total) lies in the arid (19.6%), semiarid (37%), and subhumid (21%) regions of the country, accounting for 77.6% of India's total geographical land of 329 million ha [23]. Hence, the arid and semiarid regions together make up 56.6% of India's total geographical land. Of this, 32 m ha of land comes under arid regions, where crops and vegetation are exposed to most hostile climates. These areas are mainly spread over Rajasthan, Gujarat, Karnataka, and Andhra Pradesh, with some areas in Haryana, Punjab, and Maharashtra. These areas receive only 100–500 mm of rainfall per annum and are characterized by high temporal variability which is erratic in nature due to extreme temperatures and high wind velocity on poor sandy soils. However, both semiarid and arid regions face the challenge of producing more per unit area under highly uncertain and scarce sources of water. Therefore, drought management is important to sustain agriculture and national food production.

23.1.2 Drought in the Context of Climate Change

During extremely weak or deficient years of the S-W monsoon, arid areas extend into the semiarid areas down to the peninsular region in south India. The projected impacts of climate change [25], namely rising temperature, increased erratic rainfall, long dry spells, more frequent and extreme weather events, and increased occurrence of natural hazards, among others, are expected to exacerbate the existing situation both in the arid and semiarid regions of India. Therefore, in the coming decades, these regions are going to suffer from increasing moisture stress, and become more vulnerable due to the direct impacts of climate change as well as a lack of preparedness by the state and resource-poor farmers, most of whom are small and marginal landholders.

23.1.3 Geographical Spread of Drought in India

Approximately 68%–70% of India is perennially prone to drought. Of the total land area, 33% is classified as chronically drought-prone area, and receives <750 mm of rainfall on an annual basis. Another 35% is classified as drought-prone area, and receives between 750 and 1125 mm of rainfall annually. Most of these two categories of areas are confined to peninsular and western India, primarily representing arid, semi-arid, and subhumid regions (Figure 23.1).

Globally some 2.1 billion ha falls under the semi arid tropics (SAT) region, of which 19% falls in India, supporting some 56% of the total Indian population. Fortunately, the semiarid region in India is predominantly covered by vertisols, which have a greater potential of increasing yields if moisture storage were improved and their availability increased. Therefore, farm productivity of these regions needs to be enhanced by following dryland farming techniques, which include both field- and farm-level soil and water conservation practices, and the introduction of a perennial component (e.g., fruit trees) onto the farmland on bunds and as alleys, and in agri–horti systems [11]. The following sections discuss more about these aspects, among others.

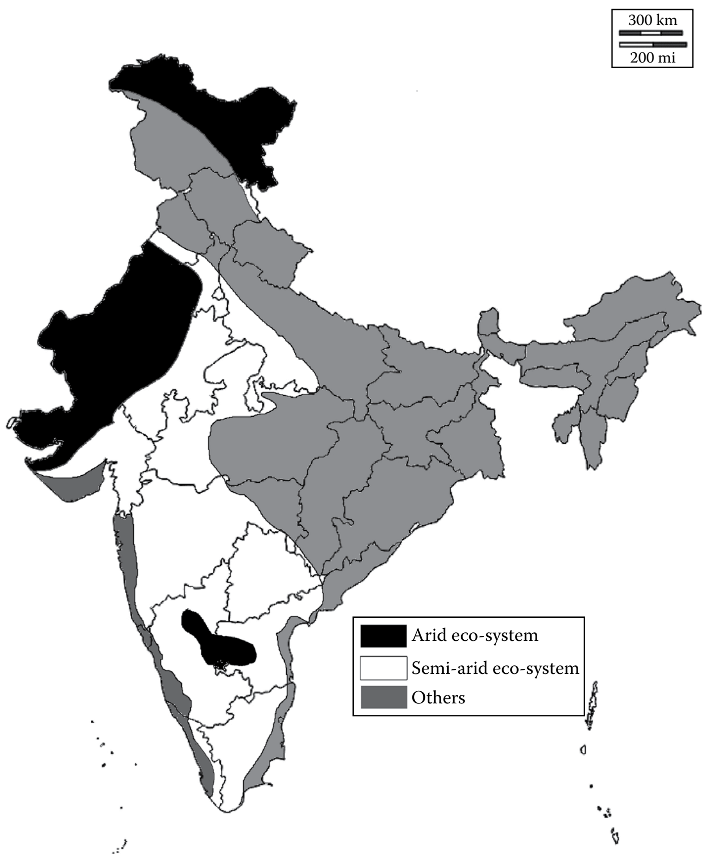

FIGURE 23.1 Geographical spread of arid and semiarid regions in India: dark shade, arid region; light shade, semi-arid region; and medium shade, others.

23.2 Why Horticultural Tree Crops?

Historically fruits have always been part of the human diet as they are rich in nutrients and provide some of the essential minerals and vitamins, and apart from that, they also help in curing a number of diseases. Globally, India is the second largest producer of fruit crops, but the per capita availability of fruits is still very low. Given the present and projected population growth, there is an urgent need to increase production of food grains (cereals, pulses, and oilseeds) as well as fruits and vegetables. The government of India (2001) estimated that fruit crops in arid and semiarid regions cover far smaller than the expected area and it has to expand by at least 60% by 2020 [1]. Fruits crops are very important as they supplement nutrition (health crops) and income, as well as insuring agriculture production systems against erratic rainfall and drought owing to their perennial nature. Crop yields in dry regions are not only low but prone to frequent failures due to erratic and uncertain monsoons, thus resulting in very high interannual variability in crop yields and farm income. In this context, the introduction of dryland fruit crops could help not only stabilize farm income and support farm families with fruits, fodder, and fuel wood, but also help beat drought to a great extent. In fact, hot and dry climates favor the production of high-quality fruits and many other underutilized crops (Table 23.1).

23.2.1 Risks with Arable Production Systems

Arable cropping systems of arid and semiarid regions of India are often subjected to aberrations of monsoon like late onset, early withdrawal, prolonged dry periods, and large variability in intra- and interannual temporal distributions of rainfall, thus resulting in either complete or partial failure of crops or rendering the arable system uneconomical. Therefore, alternative land use systems integrating perennial components are essential not only to overcome adverse weather conditions by bringing in stability and resilience to the systems, but for efficient utilization of natural resources to meet the requirements of farmers without deteriorating land productivity. Field crops like pearl millet, sorghum, green gram, cowpea, black

TABLE 23.1 Suitable Fruit Crops and Varieties for Dryland Regions

Tree Crops	Botanical Name	Improved Cultivars
Aonla	*Phyllanthusemblica* (*Emblicaofficinalis*)	Kanchan, Krishna, Narendra-7, NA-10 (Balwant); NA-7 (Neelam), NA-6 (Amrit), NA-4 (Kanchan), Chakaiya, Banarasi
Ber	*Zizyphusmauritiana*	Gola, Seb, Umran, Banarasi, Karaka, Kaithli
Bael	*Aeglemarmelos*	Narendra Bael-5, Narendra Bael-9
Custard apple	*Annonasquamosa*	Balanagar, ArkaSahan
Fig	*Ficuscarica*	Deanna, Excel, Poona, Black Ischia
Guava	*Psidiumguajava*	Allahabad Safeda, ArkaMridula. Lucknow-49, Sardar
Jamun	*Syzygiumcuminii*	Locally available and adapted ones
Karonda	*Carissa carandes*	American red and green
Lime	*Citrus limettoides*	Rangpur, Cleopatra, Tenali, Promalini, Vikram
Mango	*Mangiferaindica*	Bappakai, Banganpalli, AlampurBenishan, Neelum, Mallika, Bombay Green, Amrapali, Kesar, Dassheri
Papaya	*Carica papaya*	Coorg Honey Dew, Pusa Delicious, Pusa Majesty, Pusa Dwarf, Taiwan
Passion fruit	*Passifloraedulis*	Kaveri
Phalsa	*Grewiasubinequalis*	Locally popular ones are better
Pomegranate	*Punicagranatum*	Ruby, Ganesh, Jyothi, P-26, Jalore, Muskat, Dolk
Sapota	*Achraszapota*	Cricket Ball, Kalipatti
Sweet orange	*Citrus sinensis*	Mosambi, Kodur Sathgudi, Valencia, Blood Red, Malta
Tamarind	*Tamarindusindica*	PKM-1, Pratisthan, Yogeshwari, Anantapur local

TABLE 23.2 Rain Water Use, Loss, and Balance (All in mm) in Rainfed Environment under Three Different Land Use Systems

Land Use	Runoff	Water Infiltrated	Total Water in the Soil Profile	Water Retained in the Soil at the End of Monsoon	Water Used (Monsoon)
Bare soil	782	324	671	410	261
Grass cover	372	734	1143	741	402
Trees + grass	66	1040	1276	657	619

gram, cluster bean, moth bean, and sesame can be integrated well with different fruit crops. This would enhance production and ensure ecological stability and resilience. This can be achieved through improved efficiency of land resource use, enhanced interception of solar radiation and rainfall, and reduced soil erosion, thus increasing overall biological efficiency both in time and space (Table 23.2).

23.2.2 Selection of Fruit Trees

Drought management in horticulture fruit trees begins with a selection of tree types and cultivars suited for a given location. Identification and adoption of improved varieties with high yielding potential for dry regions as well as better performance in marginal and/or degraded lands has been done and is still being done. Such varieties can withstand not only hot and dry climate but erraticity in monsoon. The list of trees and cultivars that could be grown in arid and semiarid regions of India is given in Table 23.1. This is not an exhaustive list but includes most of the fruit tree crops and popular varieties. However, for any chosen fruit tree, the cultivar should have (1) deep tap root system to exploit deeper soil layers for water and nutrients, (2) early establishment and fruit-bearing capacity, (3) branching habit that allows maximum light penetration to the under-story field crops, (4) faster response to pruning, and (5) resistance to pests and diseases [12]. The following section provides a brief description of some fruit crops best suited for arid and semiarid regions of India.

23.2.3 Fruit Tree Crops Suited for Arid and Semiarid Regions of India

Indian gooseberry (*Emblica officinalis* Gaertn.): Indian gooseberry (aonla) is a nontraditional fruit native to India known for its drought tolerance potentiality when cultivated on marginal lands. It is now emerging as an important fruit crop known for its rich content of ascorbic acid (vitamin C) and antioxidant values. It also has medicinal value as dried aonla is used to treat dysentery, jaundice, and cough. Today, aonla products are found in both domestic and overseas markets in a variety of value-added products (e.g., candy, jam, squash, pickle). The relatively low cost of the product as well as its nutritional, medicinal, and shelf-life qualities point to the fact that processed aonla products have the potential to be explored on a commercial scale [17], which needs to be exploited by farmers from arid and semiarid regions.

Indian jujube (*Ziziphus mauritiana* Lamk.): Indian jujube (ber) is a traditional and important perennial fruit tree of India most suited to dryland regions because of its xerophytic nature and can also grow under high levels of salinity. In fact, it is an ideal fruit tree for arid and semiarid regions of India. Rightly so, it is regarded as the king of arid zone fruits and also as the poor man's apple. It is not only deliciously sweet but rich in nutritive value and is one of the richest sources of vitamin C only next to aonla and guava. In addition, it also contains fair amounts of vitamin A and B, calcium, and phosphorus [4,26]. Further, the ber tree provides fodder (leaves) to sheep and goats after each pruning and the twigs are used as fuel. Like aonla, ber fruits are also used to prepare jam, chutney, candy, and beverages of value-added products. In fact, it is the only fruit crop that gives good returns even in years of extremely low rainfall, and is thus a suitable choice for drought-prone areas.

Custard apple (*Annona squamosa* L.): Custard apple (sitaphal) is one of the most delicious fruit crops cultivated in India under dryland conditions. It is known for its easy establishment and fast growth on varied landscapes; it can be grown in forests, wastelands, rocky slopes, and other noncultivated places with minimum care and management, which makes it the best choice for dry regions to introduce on the farm [27].

Indian cherry (*Cordia myxa* L.): Indian cherry (lasodai) is another important fruit plant suitable for arid and semiarid regions of India. Its fruits and other parts have multiple benefits for human health and nutrition and other uses as well [24]. Green unripe fruits are used as fresh vegetable and to make pickles during summer when other vegetables are in scarce supply. Because of its vegetative cover it helps prevent soil erosion while offering least competition to field crops during rainy season as it produces fruits during summer. It also helps conserve rain water and requires supplemental irrigation only for 2–3 months during summer for higher yield.

Pomegranate (*Punica granatum* L.): Pomegranate (anar) is an economically and medicinally important commercial fruit crop of arid and semiarid regions. Large-scale commercial plantations of pomegranate exist in Maharashtra, Gujarat, Rajasthan, Andhra Pradesh, and Karnataka owing to its excellent preference for arid climate. Its xerophytic characteristics and hardy nature make this fruit tree best suited for dry, rainfed, and undulating land, where other fruit crops fail to perform well. Apart from being a favorite table fruit it is used for the preparation of juice and squash. Its seeds also have medicinal value and the rind is used for dyeing cloth [7].

Indian mesquite (*Prosopis cineraria* (L.) Druce): Indian mesquite (khejri) is an important component of the farming system in Indian desert regions, but is widely adaptable, and is thus cultivated in parts of Rajasthan, Gujarat, Haryana, Punjab, Delhi, and some parts of southern India. It has deep roots and nitrogen-fixing ability, and because of its multiple economic values and suitability in agroforestry systems it is widely found in western Rajasthan. The flowers are used to make honey. This tree helps in soil improvement and stabilization of sand dunes, while the wood from it is ideal as fuel. The bark of the tree has abortifacient and laxative properties as well. The immature pods are rich in crude protein, carbohydrates, and minerals [3,28]. The pods can be powdered and used to prepare bakery items such as biscuits and cookies.

Kair (*Capparis decidua* (Forsk.) Edgew): Kair is a multipurpose, perennial, woody shrub or small tree, which grows widely without needing much care in the Thar Desert of western Rajasthan. It has many branches and is leafless and bushy, and thrives well in the most adverse climatic conditions and on poor soils. It is highly suitable for stabilizing sand dunes and controlling soil erosion by wind and water [35]. Due to its xerophytic nature it grows successfully under harsh climatic conditions. Its berry-shaped unripe fruits are rich in carbohydrates, proteins, and minerals and can be used as fresh vegetables and in the preparation of pickles. The dehydrated fruits are used in the off-season as vegetable either alone or in combination with other dried vegetables.

Karonda (*Carissa carandas* L.): Karonda is an evergreen spiny shrub or small tree suitable for arid tropics and subtropics. It grows successfully on marginal and wastelands. It can also be planted around fruit farms as a dense protective hedge. It produces a heavy crop of berrylike edible fruits rich in vitamin C, minerals (Fe, Ca, Mg, P), and pectin, and the latter makes it suitable for pickles. It can also be exploited to make jelly, jam, squash, syrup, and chutney, which are gaining popularity both in domestic and international markets [40].

Bengal quince (*Aeglem armelos* (Linn.) Correa): Bengal quince (bael) is an indigenous hardy fruit crop known for its nutritional and therapeutic properties, and can be grown successfully in dry areas. The ripe fruits are used as laxative and the unripe ones are prescribed for diarrhea and dysentery, thus gaining greater demand in Ayurvedic medicine. The *marmelosin* content of this fruit is also used to treat stomach ailments [34].

Kinnow mandarin (*Citrus reticulate* Blanco): Kinnow mandarin is classified as a citrus fruit obtained by crossing King (*Citrus nobilis*) with Willow leaf (*Citrus deliciosa*) and is extensively grown in Punjab and Rajasthan. Owing to its golden orange color, high juice content, rich source of vitamin C, excellent flavor and taste, easy peeling nature, this fruit has gained economic importance and export demand [16].

Kachri (*Cucumis callosus* (Rottl.) Cogn): Kachri, another drought-hardy short-duration cucurbit vine, grows naturally, and can thus be cultivated with rainfed crops. It flowers after 30–35 days of sowing, needing minimum care, and on average produces 4–5 kg of small-sized edible fruits per vine of high nutritive value. These fruits are rich in minerals (Ca) and are generally stored round the year as whole dried fruits, dried slices, or as powder form for various uses. Further, owing to its short duration, it is generally grown in all farming systems in combination with other rainy season crops without minimum competition [17].

Tamarind (*Tamarindus indica*): Tamarind (imli) is best known for its drought resistance and can survive with minimum care and serves as insurance against drought on marginal soils of resource-poor farmers in dry regions. It bears heavily in alternate years and continues for up to 60–80 years. Tamarind seeds are rich in protein and a good source of tannins, which is why it is used in the leather industry [6].

Mango (*Mangifera india*): Mango (aam) is also called the king of fruits in India for its sweetness and extent of spread across India in varied climates. India has one of the largest varieties of mango in the world and is the largest producer of mangoes, contributing more than 44% of total global production. Within India, mango alone makes up 36% of total fruit area and little over 20% of total fruit production [2].

Sapota (*Achras sapota* L.): Sapota is mainly cultivated in India for its fruit value, while in south-east Mexico, Guatemala, and other countries it is grown for the production of chickle, a gumlike substance obtained from the latex used in making chewing gum. It is an energy-rich fruit with high total soluble solids (20%–22%) and a good source of digestible sugar, along with protein, fat, fiber, and minerals like calcium, phosphorous, and iron [33]. In India, sapota is extensively cultivated in Maharashtra, Gujarat, Karnataka, and Andhra Pradesh [38].

Apart from the fruit tree species described here, there are many other fruit trees like guava, jamun, lime, lemon, and papaya among others which could be grown under dry regions.

23.2.4 Tree Planting Time and Method

The method and time of planting tree saplings greatly influence how fast saplings establish new roots and penetrate into the soil under new environments and start contributing to biomass. Seedlings/grafts of chosen fruit species should be procured either from the State Agricultural Universities, government nurseries, or government-approved and reputed plant nurseries. Seedlings should be healthy, uniform in size, and of good quality. Care should be taken to cause no physical damage to the saplings during transportation and to water them regularly till they are planted on the main field. Planting needs to be done at the onset of monsoon or early during the rainy season (July–August) when the soil is completely wet. However, this requires that pits of proper size (2 × 2 × 2 ft L × W × D) dug at specified spacing and design, and are filled with a proper mixture of native soil, compost, and green leaf manure. Pits filled with this mixture should be left to settle down and get wet during the first rains before transplanting the saplings. After correct root placement, good compaction of soil around the seedlings has to be done to eliminate air pockets and each sapling should be tied to a bamboo or wooden stick pierced vertically next to the sapling for physical support. Each pit should be watered regularly if there are extended dry spells and the soil surface at the base is covered with dry weed or crop residue as mulch. On hilly or undulating lands, planting fruit trees along the contour is desirable and if the slope is excessively steep, 5%–6% trenches along the contours with a mild gradient need to be constructed as they would help reduce runoff and a wet soil profile.

Fields should be kept free from weeds and wild bushes, if any, with tillage operations (ploughing or harrowing) or manually. The spacing between the trees will vary from one fruit crop type to another depending on their spread and how tall they grow. For example, for fruit trees like custard apple or ber, planting at 5–6 m between rows and plants would seem just fine. In contrast, for trees which grow bigger and wider, namely mango and jamun, a distance of 8–10 m would be better. However, with high-density planting techniques, even closer spacing could be followed provided compact type of varieties are chosen and timely pruning is done at regular intervals during later stages of tree growth.

23.3 Scope of Integrating Fruit Trees with Seasonal Crops

Considerable changes in global agricultural production have occurred in response to the growing demand of the population. These changes have seen both intensification of production systems and extension to poorer and marginal lands. Given the high risks faced by farmers in dry regions, perennial fruit tree–based production systems are now considered as the most ideal component to beat drought and the risks of complete crop failures while providing food, nutrition, and income security to farmers. However, intercropping of seasonal arable crops with woody perennial species is not a new concept and is practiced in traditional farming systems in dry regions. This is one of the alternative approaches to sustain the agricultural production and stabilize the rural economy in the region. Suitability of intercrops, however, depends on a number of factors, namely, type of fruit tree, its spacing, age, soil type, climatic conditions, compatibility between arable crops and fruit trees, and other drought management practices and techniques. Fruit trees that are perennial in nature are deep-rooted and hardy compared with seasonal crops. Therefore, planting fruit trees guarantees minimum returns even during drought years when all other crops fail. Further, being perennial in nature fruit trees efficiently utilize stored soil moisture or rainwater after the seasonal crop is harvested (post-rainy and summer) during off-season rainfall in addition to the rainfall during the cropping season. This helps improve the productivity of the land, generate round-the-year employment to farming families, improve economic conditions of the farmers and entrepreneurs, enhance trade and exports, and, above all, provide nutritional security to the farming family, village, and public at large. Therefore, integrating fruit trees species onto the farm provides one of the few viable and most attractive alternative land use systems to beat drought and climatic risks while increasing the overall income per unit area (Table 23.3) [3,9]. Similar benefits from other dry regions have been shown by other workers as well (Tables 23.4 through 23.6) [41]. Therefore, large-scale introduction and cultivation of drought-hardy horticultural and medicinal tree species suited for these regions is urgently required.

23.3.1 How Do Agri–Horti Systems Work?

Fruit trees, which are perennial in nature and which grow slowly initially after planting, take at least 4–8 years to get established and cover up space between tree rows with their vegetation. During these initial years, if the space between tree rows is left barren it will not only increase water and soil erosion after each

TABLE 23.3 Yield of Different Fruit Crops under Different Agri–Horti Systems

	Yield (q/ha)		
Treatment	Aonla	Ber	Karonda
Aonla + ber + karonda + clusterbean + eggplant	8.00	85.03	43.74
Aonla + ber + karonda + clusterbean + fallow	7.81	84.68	44.06
Aonla + ber + karonda + moth bean + mustard	8.04	86.52	43.59
Aonla + ber + karonda + moth bean + fallow	7.73	84.60	43.90
Sole aonla	2.57	—	—
Sole ber	—	56.32	—
Sole karonda	—	—	19.68
C.D. (p = 0.05)	0.83	4.08	2.84

Note: 1 q = 100 kg.

TABLE 23.4 Grain Yield (q/ha) of Three Winter Field Crops Intercropped with Ber Tree Species

Cropping System	Chickpea	Wheat	Safflower
Ber + Intercrops	7.55	6.80	8.47
Sole field crops	8.00	7.92	9.30
S. Em (±)	0.20	0.28	0.17
C.D. (p = 0.05)	NS	0.83	NS

TABLE 23.5 Economic Yield (q/ha) and Monetary Returns Under Different Ber-Based Cropping Systems in Comparison to Only Sole Field Cropping Systems

Treatments	Ber Fruit Yield (q/ha)	Field Crop Yield (q/ha)	Net Income (Rs/ha)	B/C Ratio
Ber + chickpea	28.50	6.62	17,520 = 00	3.66
Ber + wheat	27.24	6.13	14,025 = 00	3.38
Ber + safflower	26.14	7.71	16,485 = 00	3.58
Sole ber	27.12	—	12,250 = 00	4.04
Sole chickpea	—	7.64	5,630 = 00	2.97
Sole wheat	—	7.28	2,200 = 00	2.07
Sole safflower	—	8.69	5,485 = 00	3.11
S. Em. (±)	1.18	—	543	—
C.D. (p = 0.05)	NS	—	1,569	—

Note: 1 q = 100 kg.

TABLE 23.6 Economics of Alternate Land Use Systems

Alternative Land Use Systems	B/C Ratio
Agri–horticulture with ber	5.00
Agri–silviculture	2.00
Arable crops	1.20–1.75
Dryland Mango	3.21
Dryland Guava	3.04
Dryland Sweet Lime	2.89

Frainy event, thus retaining less moisture in the soil profile, but also enhance the rate of stored moisture from the bare soil and expose the fruit trees to moisture stress during post-rainy and summer months (Table 23.2). Further, leaving the land between tree rows barren makes no economic sense as the inclusion of suitable intercrops during rainy season helps minimize losses and gain additional income.

On medium to deep soils with good water-holding capacity or with a well-distributed rainfall pattern, in a semiarid region or with supplemental irrigation (bore well or open well) during the critical crop growth period that coincides with flowering and grain filling, it is possible to grow a large number of crops suited for arid and semiarid regions. For example, studies on Indian gooseberry, Indian jujube, pomegranate, custard apple, guava, and mango fruit trees in dry regions have clearly shown no adverse effects on rainy season crops during the initial 4–6 years and the total productivity from agri–horti systems (intercropping) was higher than mono-cropping of only fruit trees or rainy season crops. For instance, economic analysis of agri–horti systems based on Indian jujube and Indian gooseberry done elsewhere has reported the highest net profit and cost/benefit (B/C) ratio from Indian jujube + cluster bean system followed by Indian jujube + green gram (Table 23.3). Similarly, at different dry regions, pearl millet, green gram, black gram, pigeon pea, castor, and other pulse crops can be grown between fruit tree rows [10].

Studies carried out at Central Research of Dry Land Agriculture (CRIDA), Hyderabad [8], India, have shown that leguminous intercrops (peanut, green gram, black gram, etc.) can be successfully grown in mango orchards up to at least the initial 8 years after planting with no or minimum reduction in yields of rainy season crops. Studies from Karnataka, India, have shown the possibility of growing finger millet, pearl millet, and fodder sorghum in young mango plantations. However, during subsequent years (>5–6 years), tall-growing crops like pearl millet, sorghum, and cluster bean were adversely affected and the effect was seen up to 2.5 m away from tree rows [36], that is, 2.5 m from both sides of each tree row. Therefore, during later years (>5 years), intercropping short-stature and short-duration crops like green gram, black gram, cowpea, lentil, and horse gram would not only cover the space between tree rows to reduce soil evaporation and smother weeds, but add nitrogen to soil and provide the much required nutritive fodder to animals [19]. On light sandy and marginal soils from extremely dry regions, however, growing intercrops may not be feasible, but under such situations hardier cover crops could be grown. For instance, short-statured leguminous cover crops, namely *lobia* (*Dolichosbiflorus*) and *stylo* (*Stylosantheshamata*) could be grown, which cover soil surface between fruit tree rows to reduce seasonal evaporative losses while adding organic matter and nitrogen to the soil, thus increasing the water-holding capacity and fertility of soils in dry regions in the long run to build up drought resilience.

23.3.2 Economic Performance of Agri–Horti Systems

Reddy and Sudha [30] carried out a survey in 100 randomly selected guava and mango orchards (min. 1.5 ha in size) intercropped with rainfed peanut, sorghum, vegetables, sugarcane, and turmeric in semi-arid conditions of the formerly united Andhra Pradesh state in India and found that these systems were more viable and profitable than growing fruit trees alone (Table 23.4). Once the fruit trees get established and start bearing fruit, well-maintained and established orchards give more returns than field crops from the same piece of land. Therefore, rainy season crops can be intercropped during the early stages with fruit trees. This would also generate more employment round the year. Fruit tree plantation also opens up opportunities for fruit-based industries, namely fruit processing, canning, preservation, dehydration, essential oils, packaging, transport, and refrigeration. Fruits are called protective foods owing to their rich content in essential mineral elements, vitamins, enzymes, and medicinal properties, and are thus necessary for nutritional security. Many fruits are a rich source of energy-giving carbohydrates. For instance, pectin and cellulose found in several fruits stimulate intestinal activity in the human body.

23.3.3 Multiple Benefits of Agri–Horti Systems

With the growing population on the one hand and shrinking per capita land availability on the other, pressure on land and dwindling natural resources will increase dramatically, thus requiring an increase in productivity per unit of land and time. Intensive agriculture under mono-cropping and/or under only seasonal crops is slowly but surely degrading our soils. According to one report, one-third of the total arable land in India is classified as degraded as it is affected by some soil-related problems, namely salinity, alkalinity, or waterlogging. This calls for agricultural diversification by including locally feasible multiple enterprises like growing fruit crops with field crops (agri–horticulture system), raising cattle on the farm, and recycling farm by-products and wastes as input to the farm, among others. In other words, Integrated Farming System (IFS) models, agroforestry systems, agri–horticulture systems, and alley farming seem to be the solution to manage droughts while sustaining farm productivity and natural resource base. In such situations, introducing tree components, especially fruit tree crops, will not only help reclaim soil, but also increase farm productivity and supply a variety of dietary components to the population at large.

Research studies carried out elsewhere have clearly shown that the introduction of tree crops onto arable land as hedgerow planting or along the slope can stem soil and water erosion, positively enhance the microclimate, help manage weeds better, improve crop productivity, soil fertility, and nutrient cycling, and reduce interannual variability in productivity to beat climatic variability and achieve sustainability. In addition to these benefits, trees on a farm, in the long run, help build soil organic matter (SOM) and sequester carbon to mitigate climate change. Perennial tree components with their multiple products (fruits, firewood, litter as manure, and fodder) also help stabilize farmers' income during drought years. More often than not, growing only seasonal crops in dry regions characterized by erratic rainfall exposes the soil to direct sunlight and increases evaporative loss of water from the soil surface in addition to possible erosion and runoff. Studies from the Middle East and West Africa have shown that soil moisture losses via evaporation may account for anywhere between 30% and 60% of the total annual rainfall. This is quite a significant amount and can be avoidable to a great extent (if not completely). Therefore, tree litter on the farm helps reduce soil temperature and the direct impact of raindrops on soil, enhances infiltration rate while reducing evaporation losses, and thus changes the microenvironment in favor of crops.

One of the studies in India observed that the best cropping system under dry regions may, at the most, use only 40% of the total annual rainfall, which means up to 60% of the total annual rainfall is lost through runoff, evaporation, or deep percolation. This loss could be reduced to a great extent if proper *in situ* soil and water conservation practices are followed. One of them obviously would be planting trees along bunds or along the slope or following alley farming with horticulture tree species. It is proved beyond doubt that overall productivity and resource use efficiency of the land could be enhanced with the introduction of perennial tree components compared with growing only arable crops. Introduction of trees on arable land adds plenty of litter to the soil, helps capture solar light energy more efficiently, and extracts soil water and nutrients from the deeper root zone in comparison to seasonal crops [21].

23.4 Land and Soil Management against Drought

The arid and semiarid regions of India show huge diversity in soil types ranging from deep black vertisols to sandy and shallow light soils. These soils are exposed to hot and dry climates during most of the post-rainy season. Low and erratic rainfall patterns result in relatively very low yield and total biomass production. Historically poor management of these soils by the predominately resource-poor small and marginal farmers has resulted in widespread land degradation and erosion of soils. Therefore, these soils are characterized by low infiltration rates, high runoff potential, surface crusting, and low fertility, among others. Further, the pressure from human and animal populations for their multiple needs makes it difficult to maintain or retain enough crop residue on the field as a source of organic matter, thus most soils in arid and semiarid regions contain low organic matter and fertility status. For instance, crop residues of various crops and trees have greater alternative demands as animal fodder, firewood, and thatching material for rural huts. However, following the agri–horticulture system, farmers do have the opportunity to grow field crops between tree rows and use their residues as mulch or for incorporation. This not only helps control weeds but also improves SOM, water-holding capacity, and fertility, thus building drought resilience of soils in the long run [10]. These practices in the long term help overcome poor monsoon, water deficit, and drought-like situations to a great extent while producing better yields and sustaining farmers' income.

Trees add litter regularly and thus help add organic matter to the soil and improve soil fertility on a long-term basis. Perennial trees with their vegetative crown reduce wind speed, intercept rainwater to reduce its direct impact on soil surface, but increase infiltration, whereas the dead leaves falling on the surface act as mulch to reduce raindrop impact, thus helping soil conservation. The research studies conducted on tree + crop system during the 1980s at ICRISAT, India, have shown increased conversion efficiency of natural resources, thus ensuring better performance even in extremely dry seasons. In another study, the tree + crop system was shown to conserve significantly more rainwater (Table 23.3) by reducing runoff compared with bare soil and grassland alone.

23.4.1 Land Leveling

Land should be leveled (cut and fill method) and bunds constructed at regular intervals across the slope for easy operation and efficient management of rainwater. Leveled lands enhance infiltration time of the water, thus increasing deeper soil profile wetting, which in turn reduces runoff and soil erosion. With increased and easy access to large-scale machineries for earth moving, land leveling and bunding operations have become easy and cost-effective.

23.4.2 Tillage Operations

Tillage operation if not done at an appropriate time and method encourages soil erosion. Tillage should always be done across the slope (along the bund/contours) well before the onset of the monsoon to catch as much water from one or two early showers as possible. This not only helps the wet profile but also eases the following tillage operations (harrowing etc.) for land preparation. In arid and semiarid regions, creating ridges and furrows across the wind direction or major slope has been found to reduce erosion during the summer months. Deep tillage has been found to improve the soil moisture storage, water use efficiency (WUE), and grain yield of arable crops, but of late the concepts of soil lunching, crop residue retention, and minimum tillage are being popularized, which need to be adopted for efficient utilization of rainwater.

23.5 Water Management Methods

The arid and semiarid regions are characterized by low and erratic rainfall with high variability in interseason and interannual rainfall distribution patterns. High temperatures and dry climates considerably push the demand for water, and crop evapotranspiration (ET) exceeds rainfall during most of the months of a year. Therefore, water is the most important but scarce resource defining the productivity and sustainability of agriculture in these regions. In addition, the increasing population and rising demand of water for nonagricultural uses are reducing the quantity of water available for irrigation. This has resulted in overexploitation of groundwater, which is also declining at an alarming rate due to a mismatch between demand and supply. Thus, efficient management of rainwater through water harvesting, conservation, and efficient utilization can help enhance farm productivity, reduce poverty, and maintain the natural resource base in the SAT regions [20,22].

Efficient use of water is a central issue throughout the world, and more so in India as it is facing severe water scarcity in different regions. The agricultural sector (for irrigation) alone consumes over 80% of the available freshwater in India and is expected to increase with further intensification of agriculture. Although India boasts of being the largest irrigated area in the world on absolute terms, the area covered by irrigation is only about 40% of the total gross cropped area. This is mainly attributed to the widespread practice of conventional flood methods of irrigation with only 35%–40% WUE as the rest is lost in conveyance, distribution, and evaporative losses. Thus, there is an urgent requirement to increase water productivity (WP) and WUE at national level, and more so in arid and semiarid regions, given their geographical spread in India.

In the future, a rise in temperature is obvious, which will directly affect ET; thus the total water required to raise a crop in any given location will only increase if no advanced water-saving methods are employed and practiced on a large scale with immediate priority. More efficient and advanced irrigation through water management methods and practices needs to be employed on a large scale to beat climate extremes and manage crops under drought-like situations [32]. Therefore, drought management to a great extent depends on how rainfall and irrigation water are managed. As the rainfall in the SAT region is low, erratic methods that enhance the total water available to crops need to be employed. Some of the methods that could easily be practiced for drought management in fruit crops are given in the following sections.

23.5.1 Drip Irrigation

Drip irrigation technology in agriculture has proved superior to other conventional methods of irrigation, more so in widely spaced horticultural fruit crops. Drip irrigation in widely spaced tree crops enables

(a) (b)

FIGURE 23.2 Drip irrigation to (a) improve water productivity and (b) water use efficiency on farms.

TABLE 23.7 Extent of Drip Irrigation for Grain and Horticulture Crops in Different States in India

	Area ('000 ha)		Percent to Total Cultivated Area	
States	1991–1992	2000–2001	1991–1992	2000–2001
Maharashtra	32.92	160.28	44.64	53.16
Karnataka	11.41	66.30	16.17	18.03
Tamil Nadu	5.36	55.90	7.59	15.20
Andhra Pradesh	11.59	36.30	16.41	9.88
Gujarat	3.56	7.60	5.05	2.07
Kerala	3.04	5.50	4.30	1.50
Orissa	0.04	1.90	0.06	0.52
Haryana	0.012	2.02	0.17	0.55
Rajasthan	0.30	6.00	0.43	1.63
Uttar Pradesh	10.11	2.50	0.16	0.68
Punjab	0.02	1.80	0.03	0.49
Other states	2.127	5.40	3.00	1.47
Total	70.59	367.60	100.00	100.00

precise and direct application of water in the root zone (Figure 23.2), but its adoptability is very limited except in states where central- and/or state-sponsored schemes are operating (Table 23.7).

This method will obviously not only help save the limited water and expand the area under protective irrigation, but precise feeding of water to root zones will also enhance growth, development, and yield of fruits. The targeted application of water to the root zone through drips also excludes weeds from accessing water, and thus their growth is controlled and easily managed (Figure 23.3).

Adoption of drips also saves labor for irrigation and weeding. The saving in water through drip is to the tune of 30%–50% depending on the tree crop and season. There is huge potential for expanding irrigation under the drip method with available water and saving large areas of fruit crop from drought-like situations while maintaining better yields. This is, however, feasible if farmers dig a bore well or an open well or have a farm pond to collect runoff during the rainy season. In fact, soil surface mulching and irrigation with either pitcher or drip method, whichever is feasible, will require less water to sustain the tree growth and fruit yield and quality.

23.5.2 Micro-Sprinkler Irrigation

Depending upon the situation and availability of water, this technology can be used for fruit crops. The cost of the initial investment is lower compared with that for the drip system. Furthermore, during the summer

(a) (b)

FIGURE 23.3 (a) Drip irrigation line around the base and (b) paired drip lines on either side of tree base.

(a) (b)

FIGURE 23.4 (a) Micro-sprinkler irrigation with mulch around tree base and (b) pitcher pot irrigation.

months, micro-sprinkler irrigation helps create a favorable microclimate by moderating the temperature while increasing the humidity, and thus improves the growth and yield of fruit crops (Figure 23.4). This method can reduce up to 20%–30% of water requirement compared with conventional irrigation, which means for every 4–5 acres of where micro-sprinkler irrigation has been adopted, one additional acre of fruit crop can be brought under micro-sprinkler irrigation.

23.6 Fertigation and Foliar Nutrition to Manage Drought

Application of water-soluble chemical fertilizers with the help of drip irrigation water further helps enhance fertilizer use efficiency and fruit tree uptake, which in turn help increase yield and quality of fruits while reducing nutrient losses. Foliar application of chemical nutrients during moisture stress conditions helps immediately overcome nutrient deficiency and enhances growth through quick absorption of nutrients. For instance, spraying of potassium (K) and calcium (Ca) induces drought tolerance in younger saplings and fruit trees. Spraying water-soluble micronutrients and secondary nutrients also helps provide a balance of nutrients required by fruit trees and improves yields and quality of produce. This also reduces to some extent pest and disease incidence.

23.7 Advanced Methods of Irrigation

Today with the global freshwater crisis looming large in many countries, and more so in India's arid and semi-arid regions, the concept of "more crop per drop" is being popularized at all levels. In this context, apart from sprinkler and drip methods of irrigation, which save significant amounts of water compared with traditional/conventional methods, there are a few new approaches devised which would help farmers to further reduce the water requirement of tree crops while maintaining yield levels. A few of them are briefly explained here.

23.7.1 Deficit Irrigation

Deficit irrigation (DI) is a concept where crops are deliberately but systematically under-irrigated (less than total ET demand) to reduce total water requirement [5,27,31]. This is done to reduce the transpiration to some extent (5%–15% depending on the crop type, season, etc.) without affecting carbon assimilation and yield. However, how much water could be saved with DI is a matter of further research study, which requires a thorough understanding of the tree crops' response to DI and of the possible impact on crop yield and quality. The potential benefits of DI, if followed properly, include (1) reduced irrigation and production costs, (2) increased WUE, and (3) the opportunity of alternative uses of water. This method has great promise in dry areas where water is the scarcest resource and has multiple demands.

23.7.2 Regulated Deficit Irrigation

Regulated deficit irrigation (RDI) is a modified method of DI developed in Australia for peach and pear orchards, which creates water stress at certain predetermined physiological stages of fruit trees to control vegetative growth and the competition between the vegetative and reproductive parts. In RDI, water is applied in quantities less than required to meet crop ET only during certain periods of the crop cycle when production and crop quality are least affected, whereas full crop ET is met at critical periods of the cycle. Further research is required to test the response of fruit trees to RDI in arid and semiarid regions [14,31].

23.7.3 Partial Root Drying

Partial root zone drying (PRD) is another method of irrigation where only one side of the root system is fully watered to meet crop ET while the other side is allowed to dry. This means both sides of the crop/tree rows are watered alternately [14]. Research elsewhere has shown that drying of one side triggers a root-shoot signaling mechanism to close the stomata partially [13]. This kind of stomatal regulation lowers crop ET losses with little or no effect on photosynthesis, but increases WUE via increased transpiration efficiency [14,15,37]. This method could very easily be adaptable on tree crops under paired row drip or regulated furrow method, one row running on either side of the tree row. Therefore, need for research studies on applicability and optimization of DI, RDI, and PRD methods for tree crops of dry regions cannot be stressed more in today's water scarcity situation.

23.8 Managing Deficit Rainfall and Long Dry Spells

Apart from the methods described, a number of other strategies are required to manage deficit rainfall and long dry spells during rainy and post-rainy seasons in fruit crops to overcome the adverse impact of drought. A few methods are briefly listed here.

23.8.1 Pitcher Pot Irrigation

The establishment stage after planting fruit saplings is a very critical one in which one must ensure that the saplings grow healthily and fast, and thus requires proper water and nutrient supply. This is the stage when saplings send their roots deep into the soil profile to provide strong support, both physically and nutritionally. If saplings are planted in dry regions without the support of irrigation, providing subsoil water supply using the pitcher (mud pot) method is recommended. A locally made earthen or plastic pot of 8–10 L capacity with a small hole at the bottom of the pot connected by a narrow tube should be placed at 30 cm depth and 15 cm away from the tree seedlings in the basin at the time of planting. After filling the pot with water, it should be covered with a lid. Water is supplied to the root drop by drop through a narrow tube (2–3 cm in diameter) to provide some 1–1.5 L of water per day, which is useful for the growth of the seedling (Figure 23.4). However, farmers need to refill these pitchers as and when they get empty. To reduce soil evaporation and smother weeds growing around the base of the saplings (3 ft in diameter), mulching locally available crop residues, namely paddy or sugarcane thrash or grass cut from the bunds, can be used. This ensures a proper supply of water while reducing limited water resources during the establishment stage and beating drought-like situations.

23.8.2 Rainwater Harvesting

Monsoon rainfall pattern in dry regions is typically characterized by long dry spells between two rainy events and each rainy event, more often than not, occurs with high intensity; thus, runoff potential is more on the farm, especially if the land is not leveled and supported by bunds across the slopes at regular interval. If land leveling and bunding seems to be a costly proposition, especially for resource-poor small and marginal farmers, any of the following measures can help harvest rainwater effectively and ensure moisture supply to fruit trees during dry periods to overcome moisture stress.

23.8.3 Construction of Farm Pond

Rainwater harvesting also includes collecting runoff water in dug-out ponds or tanks in small depressions, gullies, and storage tanks of earth or masonry structures (Figure 23.5). It is possible to collect 10%–50% of total rainfall as runoff water in dug-out ponds in areas receiving as little as 500–800 mm of rainfall. Surface runoff water thus collected in a farm pond can be used to provide protective irrigation during periods of prolonged dry spells. This would not only overcome moisture stress and drought-like situations but also enhance fruit yield and quality.

23.8.4 Circular Trenches around Trees

Opening of circular trenches around fruit trees and mulching the trenches with locally available crop residues or fallen tree leaves or grass helps catch rainwater and conserve it for the tree. Circular trenches should be dug 6–9 in. deep and wide, 5–6 ft away from the tree base (depending on the age of the tree).

(a) (b)

FIGURE 23.5 Runoff rainwater harvesting in farm pond for irrigation during (a) long dry spells and (b) summer period.

(a) (b)

FIGURE 23.6 Mulching (a) between and (b) below tree rows to reduce evaporation losses and smother weeds.

TABLE 23.8 Mulching Improves Crop Yield and WUE of Pearl Millet (CAZRI, Jodhpur, India)

Mulch	Water Use (ET) mm	Yield (kg/ha)	WUE (kg/ha/mm)
Polyethylene	279	2900	10.4
Pearl millet husk	269	2300	8.5
No mulch	291	1740	6.0

These trenches help catch running rainwater as and when it rains and conserve sufficient moisture in the soil profile, especially during flowering and fruiting to increase yield.

23.8.5 Mulching

Loss of soil moisture directly through evaporation is an important component of the total crop water demand. Up to 45% of the total water on *vertisols*, 21% on *alfisols*, and 12%–18% on *loamy sand soils* may be lost through soil evaporation, which could be reduced to a great extent by mulching. Mulching is done by spreading stubble, trash, dead weed biomass, or any other vegetation on the surface (Figure 23.6). In addition to reducing evaporation, mulching minimizes the direct impact of raindrops on the soil surface, thus increasing absorption of the rainfall, obstructing surface flow, and reducing erosion. In addition, crop residue mulch on the surface can moderate soil temperature during summer. Studies conducted in arid zones of India (CAZRI, Jodhpur) have shown that mulching improved both the water use and WUE in pearl millet (Table 23.8).

Similar effects are observed in fruit crops as well as in agri–horti systems. Spreading crop residues and dried weed biomass around the tree base and if possible between the tree rows not only enhances WP and WUE by reducing evaporative losses but also helps trees grow and yield better even during low rainfall years. Surface mulching in the long term adds organic matter to soil and helps build soil organic carbon, and hence water-holding capacity and fertility. In contrast, if farmers can afford it, covering the sapling base with black polyethylene film of 100 μm thickness in a rectangular or circular shape, keeping the sapling at the center, helps conserving soil moisture and enhances root growth. If this is done for full-grown trees, it not only helps conserve moisture and enhance rooting but also improves flowering and fruiting while reducing fruit drop, thus enhancing yield (Figures 23.7 and 23.8).

23.9 Planting Trees on the Bund as Wind Breaks

Apart from employing *in situ* soil and water conservation techniques as well as water-saving irrigation methods, the adverse effect of hot and dry climates on the SAT region during post-rainy and summer seasons can be reduced to some extent by planting tall-growing trees all along the outside boundary of the farm. For instance, planting casuarina and teak trees may help. Planting Glyricidia, for instance, would

(a)

(b)

FIGURE 23.7 (a) Plastic mulch around the base of a tree and (b) mulching with crop residues around young saplings.

FIGURE 23.8 Mulching with white polythene sheet around base and crop residues between tree rows.

also provide green leaf manure after each cutting during the monsoon and it grows back fast and can withstand frequent coppicing. Of course, intercropping of short-duration drought-tolerant field crops between tree rows, at least during the initial 6–8 years until the branches of tree rows touch each other, would also reduce soil evaporation, especially during post-rainy and summer months.

23.10 Knowledge and Skill Development on Drought Management

With the advancement in space and satellite technology, India has developed weather forecasting and drought assessment capabilities to a great extent, but there is still scope to achieve greater reliability in very short-term and long-term weather forecasting. Further, there is an urgent need to enhance capacity for early warning and impact-monitoring systems, especially in the light of climate change impacts and huge variability in temporal and spatial rainfall patterns at local levels. There is also a need to develop adequate drought-monitoring systems and the capacity to respond through proactive political, institutional, and technological machinery working in tandem top-down, which is now affecting the development of drought early warning and management capability.

In this context, several studies have underlined the importance of strengthening these capabilities and several measures have been suggested. Spread and adoption of ongoing agro-meteorology advisory services, issued on a weekly or biweekly basis, are helping farmers, but there is a need to enhance medium- and long-range forecasting capabilities. Furthermore, given the large number of farmers spread across vast areas of arid and semiarid regions, timely and effective coordination among various machineries working at the levels of village, block, district, state, and national ministries, departments, and organizations is required to improve drought management capabilities [1,19,29]. In addition to these measures, farmers from arid and semiarid regions need to be trained at advanced production techniques, namely soil and water conservation, crop management, and drought management in arid and semiarid regions, on a regular basis.

23.11 Summary and Conclusions

In arid and semiarid regions of India, droughts are a recurring phenomenon. This situation is burdened by relatively low-fertile soils owing to poor management under hot and dry climates, resulting in unsustainable production. However, given the human and cattle population pressure on these lands for food and fodder, especially in the context of climate change and its expected adverse impacts on already vulnerable agro-ecosystems, the production systems should integrate both fruit trees and seasonal arable crops in such a way that farmers get both food grains and fodder to sustain their family and cattle while earning some additional financial benefits from fruit trees. Integration of perennial trees with seasonal crops, wherever feasible, would not only help farmers earn additional income even during the worst monsoon years, but in the long run would enable the soils to build soil organic matter (SOM), control stem soil erosion, improve rainwater harvesting, while lowering avoidable losses through evaporation. This helps build resilience against extreme moisture stress and drought-like environment. There are a number of traditionally popular, nutritionally rich, and commercially viable fruit trees that are well suited to arid and semiarid climates of India. However, the choice of fruit tree depends on the soil type, local climate, and availability of irrigation water. With regard to seasonal crops, a number of cereal and pulse crops are available to choose from. In addition to integration of fruit trees and crops, adoption of advanced irrigation methods, storage and use of rainwater from farm ponds during post-rainy/summer season, application of stored or underground water for irrigation at critical stages via drip, trickle, and partial root zone drying methods, coupled with mulching and crop residue retention on the surface, would go a long way in managing drought in arid and semiarid environments.

Authors

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24

Interbasin Transfers of Water for Southern Africa

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Abstract In this chapter, interbasin transfer of water (often hyphenated) describes manmade conveyance schemes, which move water from one river basin where it is available to another basin where water is less available or could be utilized better for human development. The purpose of such designed schemes can be to alleviate water shortages in the receiving basin, to generate electricity, or both. In some cases, interbasin transfers have been undertaken for political purposes. Since conveyance of water between natural basins are described as both a subtraction at the source and as an addition at the destination, such projects may be controversial in some places, and over time they may also be seen as controversial due to their scale, costs, and environmental or developmental impacts. Water transfers seriously impact the environment of the donor basin. They create or escalate threats to critically endangered species, Ramsar-listed wetlands, and protected areas. Dam constructed on the river from which water is taken can devastate its ecology, disrupt environmental flows, and block migrating fish.

24.1 Introduction

24.1.1 Synopsis

The interbasin transfer of water from one basin to an other dates from the earliest days of civilization. The cities of Mesopotamia developed extensive systems to move water from the mountains to the low fertile valleys between the Tigris and Euphrates rivers for use in irrigated agriculture and municipal water supplies [25]. The Romans developed a complex system of aqueducts dating back to 312 BC according to Hansen [10]. These engineering feats were accomplished without environmental review or balancing competing interests and concerns.

24.1.2 Physical, Geographic, and Political Settings

Southern Africa is synonymous with Southern Africa Development Community (SADC), which is formed by 15 sovereign states (12 continental states and three island states); they include Angola, Democratic Republic of the Congo, Botswana, Lesotho, Madagascar, Malawi, Mauritius, Mozambique, Namibia, Seychelles, South Africa, Swaziland, Tanzania, Zambia, and Zimbabwe according to Msangi [17]. The regional grouping was formed in 1980 by nine continental member states at the Southern Africa Development Co-ordination Conference (SADCC).

Mainland Southern Africa comprises 11 countries, some of which are among the poorest in the world (e.g., Mozambique, Malawi, Zambia) and many of which have suffered from protracted violence (e.g., Angola, Mozambique, Republic of South Africa, Zimbabwe, and the Democratic Republic of Congo) (Figure 24.1). The region was an important theater of the Cold War: many of its civil wars during that period were localized

FIGURE 24.1 Southern Africa states (Seychelles not shown on the map). (From Malzbender, D. and Earle, A. [14]).

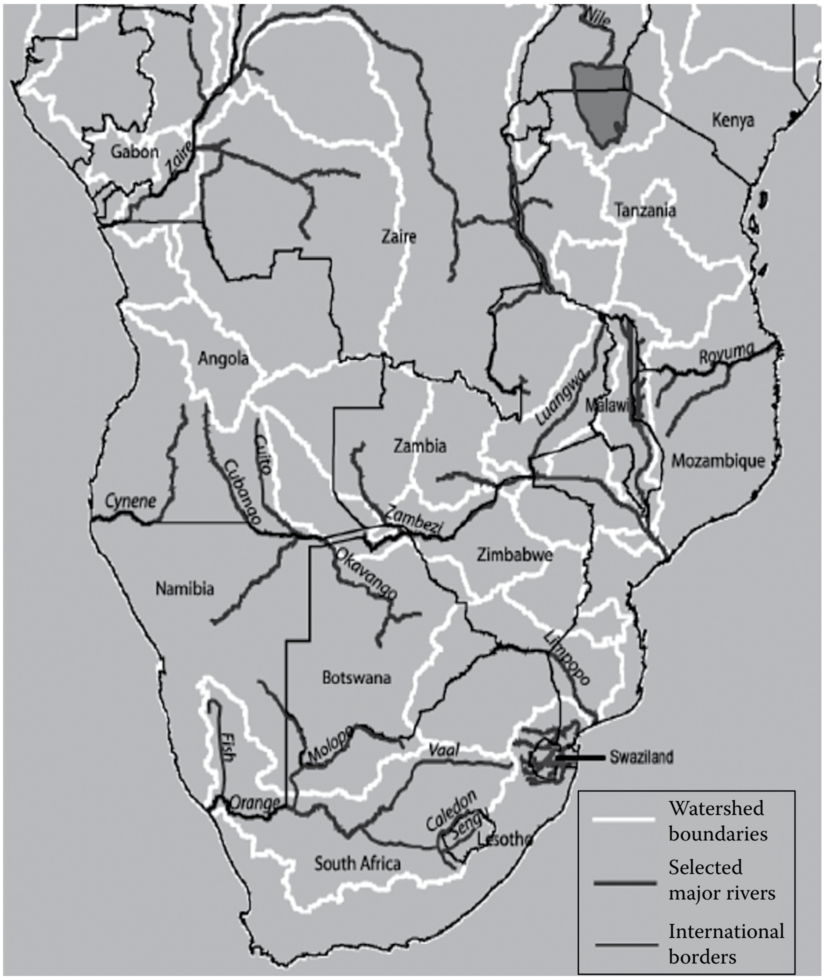

FIGURE 24.2 Map of Southern Africa, with major rivers and watersheds. (Turton, Anthony R. [24].)

manifestations of former superpower rivalries according to Turton [23]. This history has left modern Southern Africa with a complex mosaic of conflict and tension—a legacy exacerbated by environmental scarcities in one form or another. Indeed, Southern Africa is characterized by three environmentally and developmentally distinct features that act as fundamental drivers of potential conflict or cooperation.

The Southern Africa region contains 15 major internationally shared river basins (Figure 24.2). The water basins include the Buzi, Congo, Cuvelai, Incomati, Kunene, Limpopo, Maputo-Usutu-Pongola, Nile, Okavango, Orange-Senqu, Pungwe, Ruvuma, Save-Sabi, Umbilici, Maputo, Nile, Okavango, Orange, Pungwe, Ruvuma, Sabi, Umbeluzi, and the Zambezi (Figure 24.2). The water basins all vary in size, with the smallest being the Umbeluzi, which covers 10,900 km^2, while the largest is the Congo Basin, which covers 3,691,000 km^2.

24.2 South African Interbasin Water Transfer

24.2.1 Synopsis

In general, water is a finite and a scarce resource in many parts of the Southern Africa region. While in parts of the region there is seasonal water abundance, in other parts there is a perpetual deficit. Rainfall is widespread in the northwest region encompassing the Democratic Republic of Congo (DRC) and scarce in the southwest parts that include Namibia and North Western Cape Province of South Africa. The total annual rainfall ranges from less than 100 mm in the Kalahari and Namib Deserts to over 2000 mm in the north and central tropical regions of Angola and the Democratic Republic of Congo (DRC) (Figure 24.3). Water scarcity is a recognized norm in a large part of the Southern Africa region. The region has very arid conditions and variable climate, both temporally as well as spatially in the south center and south west of the continent and is subjected to highly unreliable rainfall regimes, which worsens the region's vulnerability to recurring droughts. Floods frequently follow droughts and an

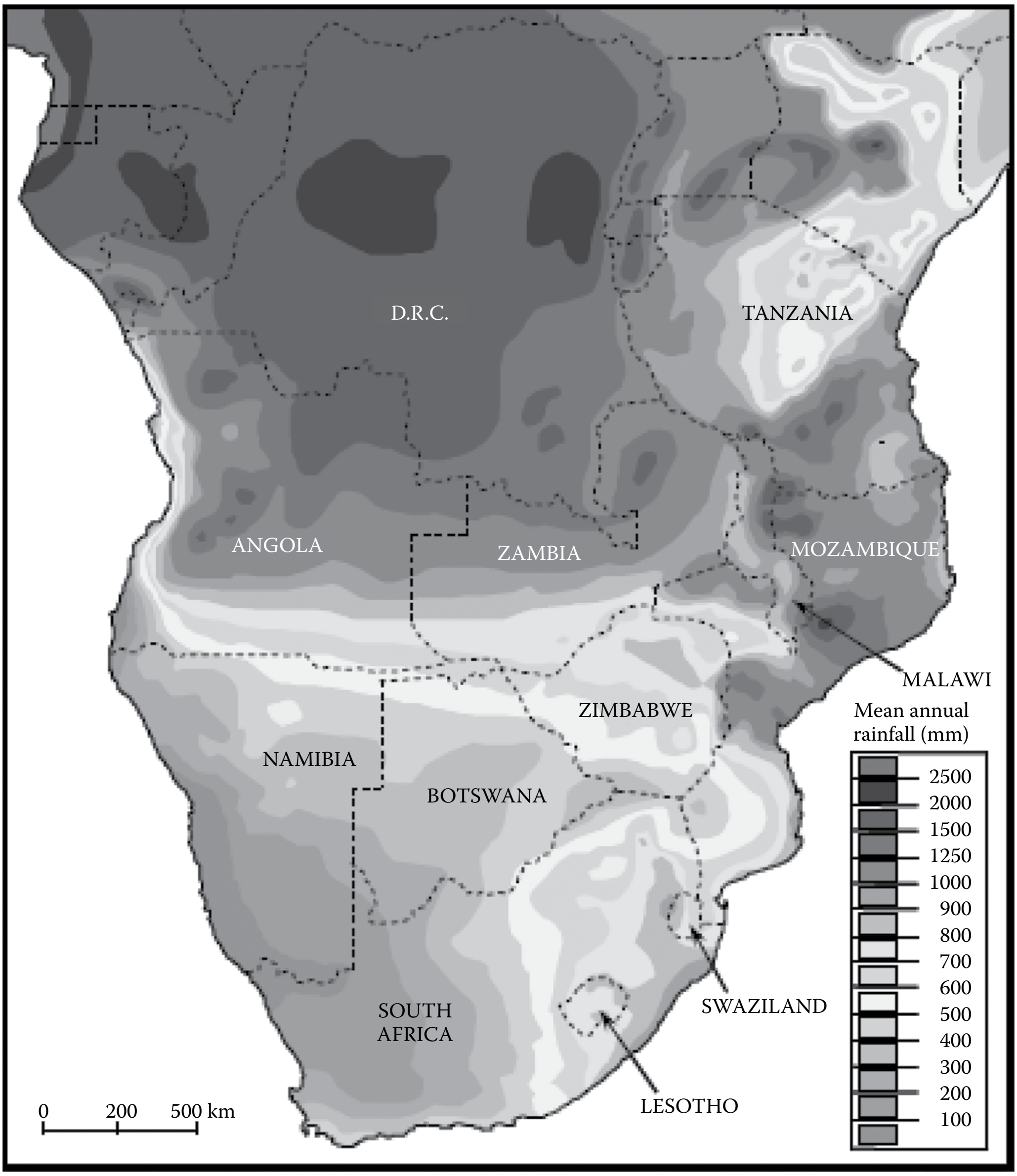

FIGURE 24.3 Spatial distribution of Mean Annual Precipitation (MAP) across Southern Africa. (Courtesy of Prof. Peter Ashton.)

average year is rare. As with most parts of the world, the impacts of climate change are debated, but it seems likely that the region will become drier over the next 50 years. The dry Southern African countries (South Africa, Botswana, Namibia, and Zimbabwe) are predicted to face high levels of water stress by 2025 according to Turton [24]. There will thus increasingly be calls for the construction of more dams and to embark on ever greater water transfer schemes (Figure 24.3). The region has unevenly distributed water resources (both temporal and spatial). This unevenness extends to both surface and groundwater resources. The bulk of the regional water resources are found in 15 transboundary water courses according to Msangi [18]. In 1991–1992, the region experienced one of its debilitating droughts; this experience appears to have been instrumental in speeding up the implementation of regional integration and water resources management strategies.

24.2.2 Statutes Regulating Water Transfers

The statutory requirements establish three basic rules: (1) the transfer causes no injury to any legal user of water according to the California Water Code, CWC [5]; (2) it must not result in any unreasonable effects to fish or wildlife based on California Water Code, 1727, 1736, 1810 [5]; and (3) if it is water from the State Water Project, the transfer must have no unreasonable economic impacts on the overall economy of the county from which the water is transferred [5].

24.3 Factors Controlling Interbasin Water Transfer in South Africa

Drought and flooding are normal events in the region's hydrological context. A number of natural cycles affect the region's rivers, for example, the Okavango River Basin has an 18-year cycle of climate variability, while records from the Zambezi Basin show the existence of an 80-year cycle according to McCarthy et al. [14]. Flood pulsing or the variability between periods of high flow and low or even nonflow periods is also recognized as a key ecological driver according to Junk et al. [13], Davies et al. [7], Gumbricht et al. [9], McCarthy et al. [15], Puckridge et al. [21], and Turton [23]. Climate variability also has a number of key environmental security ramifications: (1) the long-term impact of global climate change on both water availability and the incidence of extreme events, (2) the impact of growing populations on a relatively finite and variable water resource base, and (3) the existence of a large number of dams in order to store water during the unpredictable and often long dry periods. For example, South Africa and Zimbabwe have 752 large dams between them, while the region's other nine countries have only 55 dams among them according to World Commission on Dams (WCD) [25,26]. The region's wetter countries (such as Angola, Malawi, Mozambique, Tanzania, and Zambia) have among the lowest densities of dams in the world for nonkarstic regions, with an annual rainfall in the range of 600–2000 mm. Accordingly, a large number of international river basins, inherent climatic variability, and a natural uneven distribution of perennial rivers characterize Southern Africa. The region also has a history of political instability, driven by liberation struggles against the former colonial powers, apartheid, and the Cold War. Southern Africa's transboundary rivers and their associated ecosystems could become either drivers of peace and economic integration or sources of endemic conflict. This situation, combined with the regional development of international and increasingly complex interbasin water transfers, highlights the need to develop appropriate scientific methodologies that can shed light on future patterns of conflict and cooperation. This is pertinent to the Southern African region with such a high number of shared rivers—16 shared basins among 12 countries (Figures 24.1 and 24.2) according to Wolf et al. [27]. In conclusion, climate variability is a key determinant of Southern Africa's ecological dynamics and environmental security.

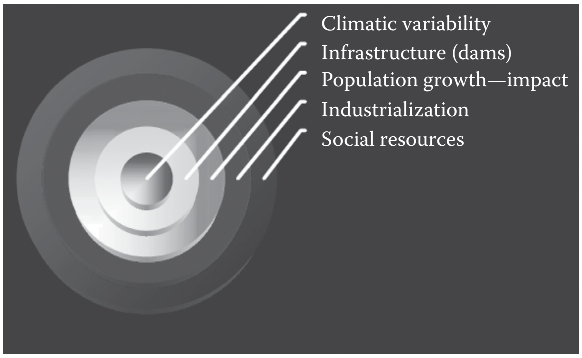

FIGURE 24.4 Variables impacting water resources management.

24.4 Key Issues Causing Hydropolitical Vulnerability in Southern Africa

According to Earle, in Southern Africa, the key issues causing hydropolitical vulnerability include[8] the following:

1. Natural climatic variability—naturally variable rainfall patterns with frequent periods of floods and drought.
2. The construction of large dams and associated interbasin transfers (IBT)—largely as a response to the previous point, in order to mitigate the impact of the natural climatic variability.
3. Population dynamics in the region—growth or decline in population size affecting the water needs of the region.
4. Economic priorities—African economies tend to emphasize resource-extractive industries such as mining and forestry (Figure 24.4). These extractive industries, if not well managed, tend to affect surrounding ecosystems negatively. At the same time, environmental legislation covering emissions into the atmosphere, soil, and water is generally either not in place or, if it is in place, frequently not implemented.
5. Social resources—these encompass factors such as institutional development, economic wealth, and systems of government, laws, and legislation and the education level of the population (Figure 24.4).

24.5 Current Situation of Interbasin Water Transfer in Southern Africa

The region's 11 mainland countries are traversed by no less than 15 international river basins (Figures 24.1 and 24.2), including such major basins as the Zambezi (which is shared by eight states) and the *Limpopo* and *Orange* (which are shared by four states each). Fed by an increasingly complex series of pipelines and water transfer schemes (which has given rise to the so-called pipelines of power), the dams of the Republic of South Africa and Zimbabwe support a vast array of economic activities according to Turton [23]. For example, the four most economically developed states in Southern Africa—the Republic of South Africa, Botswana, Namibia, and to a lesser extent Zimbabwe—also happen to be water-stressed. In fact, these four countries have already reached the limitations of their readily available water resources and now need to develop increasingly sophisticated interbasin transfers of water to sustain their economic growth potential. Following are just a few illustrative examples of such transfers:

In the Republic of South Africa—the most economically developed state in the Southern African region—interbasin transfers of water across various natural, provincial, and even international borders sustain 100% of the gross geographic product (GGP) in the Gauteng Province (Figure 24.5) and

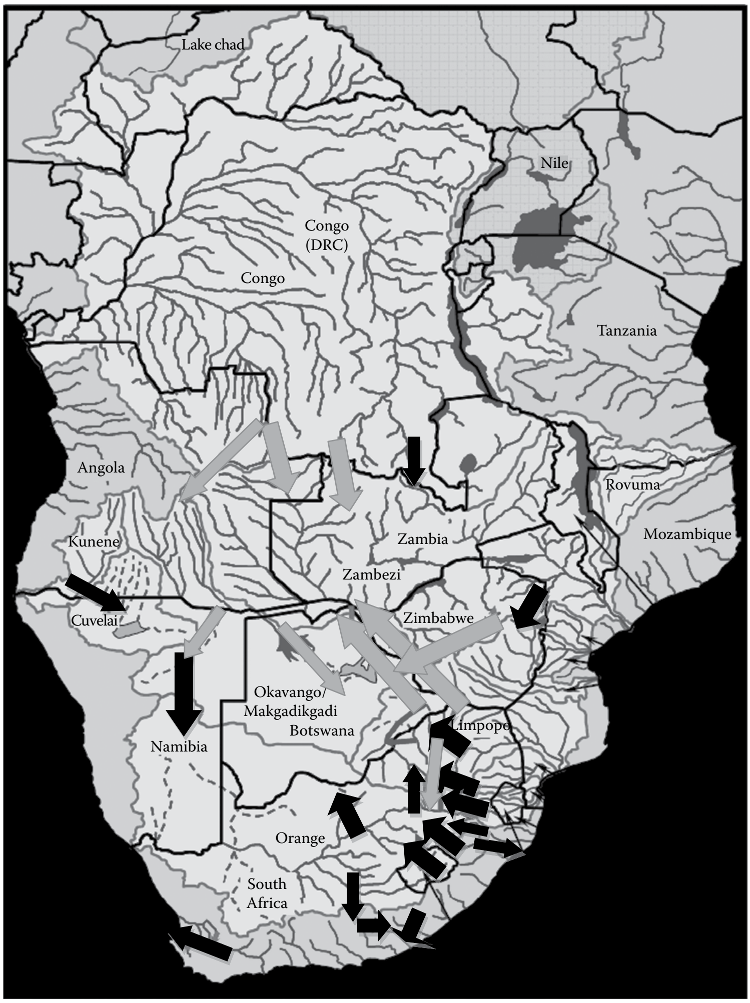

FIGURE 24.5 Existing (black arrows) and planned (gray arrows) Inter-Basin Transfers within the SADC Region designed to establish the stable water supply infrastructure needed to create sufficient assurance of supply on which future industrial growth and economic development can be built. (Courtesy of Prof. Peter Ashton.)

are responsible for more than 50% of the GGP in seven of the nine provinces according to Basson et al. [3], and Turton [5]. One of the key elements of these transfers is the Lesotho Highlands Water Project (LHWP), which transfers water by gravity to Johannesburg and Pretoria (Figure 24.5) and could also supply water to Gaborone in Botswana if needed.

Two strategic water transfers currently sustain the Botswana economy: (1) the transfer from the Molatedi Dam in South Africa according to Conley [6] and Heyns [11] and (2) the North-South Carrier in Botswana (Figure 24.5), which has a proposed future linkage to the Zambezi River according to Heyns [12].

A pipeline is planned to link the Okavango River in Caprivi Strip with Namibia's Eastern National Water Carrier, (Figure 24.5), which feeds the economic heartland around Windhoek and therefore sustains the Namibian economy [12,20]. This pipeline will become a strategic component of the overall water management strategy of Namibia but is hotly contested by environmental groups in Botswana as indicated by Ramberg [19] and Ashton and Marian [1].

Another planned pipeline would tap the Zambezi River to supply the city of Bulawayo in Zimbabwe; it could also link into the North-South Carrier in Botswana according to Heyns [12].

The possible supply of Zambezi River water to Botswana, Zimbabwe, and Gauteng Province (Pretoria) in South Africa has been under investigation at various times in the past according to Borchert [4], Heyns [12], Midgley [16], and Scudder et al. [22]. However, South Africa is not a Zambezi riparian state and would have to negotiate access through a complex set of diplomatic exchanges before this link could become reality (Figure 24.5).

24.6 Managing Water Scarcity in Southern Africa

24.6.1 Synopsis

Communities ought to be involved more in the management of water resources on which they depend. The Protocol on Shared Watercourses is seen as a formalization of the objectives and mechanisms for this cooperation, which is being adapted into bilateral and multilateral agreements between watercourse states. The cooperation is seen as a promoter of an environment of collaboration and trust between countries; it is contributing toward peace in the region.

24.6.2 River Basin Organizations in South Africa

The South African Development Community (SADC) Water Protocol is the framework governing transboundary water resources management in the SADC region. The SADC Water Protocol does not regulate the specifics of basin management in the respective basins of the region. Instead, it is a framework instrument that contains the accepted key elements of international water law and makes it mandatory for transboundary water resources management in the SADC; the elements include, among others, equitable and reasonable utilization and the obligation to give prior notice of planned developments in any of the shared basins. The SADC Protocol on Shared Watercourses and other watercourse agreements provide an opportunity to clearly outline effective dispute resolution processes negotiated by watercourse states before the conflict arises.

24.6.2.1 Congo-Oubangui Basin Commission

The International Commission for the Congo-Oubangui-Sangha Basin (CICOS) is a relatively new River Basin Organization (RBO) and was only created in 1999. The member states of CICOS are Cameroon, Central African Republic, Democratic Republic of Congo, and the Republic of Congo.

24.6.2.2 Pangani Basin Water Board

The Pangani River Basin is shared by Kenya and Tanzania and covers about 42,000 km^2. The two countries established the Pangani Basin Water Board (PBWB) and the Pangani Basin Water Office (PBWO) in July 1991 to jointly manage the water resources in the basin.

24.6.2.3 Permanent Okavango River Basin Water Commission

The three Okavango Basin states Angola, Botswana, and Namibia signed an agreement in 1994 that formed the Permanent Okavango River Basin Commission (OKACOM).

24.6.2.4 Inkomati Tripartite Permanent Technical Committee

The Tripartite Permanent Technical Committee (TPTC) is a collaboration between three SADC member states, namely, South Africa, Mozambique, and Swaziland.

24.6.2.5 Lake Tanganyika Authority

Lake Tanganyika is Africa's oldest and deepest lake and contains almost 17% of the world's available freshwater.

24.6.2.6 Zambezi Watercourse Commission

The agreement to establish the Zambezi Watercourse Commission (ZAMCOM) was signed in 2004 by Zambia, Angola, Namibia, Zimbabwe, Botswana, Malawi, Tanzania, and Mozambique.

24.6.2.7 Ruvuma Joint Water Commission

The governments of the Republic of Mozambique and the United Republic of Tanzania have very recently established the Ruvuma Joint Water Commission with the principal objective of ensuring sustainable development and equitable utilization of common water resources of the Ruvuma River basin.

24.6.3 Impact of Climatic Conditions on Water Resource Management

Climate changes will affect the initial surface runoff into stream systems, rates of evaporative loss, seepage to groundwater aquifers, recharge from those aquifers, and rates of consumptive use for irrigation along entire stream systems. Until climate change is better understood, the magnitude of these changes and estimates of reliability will be difficult to predict. Climate changes will increase the ambient air temperature in the South African states. This would result in increased evapotranspiration. In the case of transfer proposals, water authorities often limit the quantity of water transferred from an existing user to another place or type of use to the seller's historic consumptive use, to prevent impairment of other water rights. For example, half of the water diverted to an irrigated field might currently be lost to evapotranspiration while the remainder returns to a useable water body. If the rights were transferred, the buyer's diversion right would be established to allow expected consumption equal to half of the original diversion right according to Miller et al. [16]. The prospect of climate change makes it difficult to forecast future uses and availability of water and to keep the existing supplies reliable. Once climate models are scaled to specific watersheds, existing laws will have to be applied to resolve future conflicts. For example, the law prohibiting waste and unreasonable use could be used to address site-specific reevaluation of water use on a case-by-case basis. The public trust doctrine also allows for the reexamination of past allocation decisions, where a change in circumstances or a passage of time warrants the review according to Attwater and Markle [2].

24.6.4 Social Impact on the Management of Water Resources in South Africa

On a transboundary level, where a water supply is shared between two or more states, social resources become an effective tool in the promotion of cooperation over the water resource. They do this by shifting the debate away from pure water sharing (my rights vs. your rights) to a benefit sharing approach. Thus, water becomes one component in a basket of benefits, which can be shared between parties. This would see a resource such as the Okavango Delta wetland conserved through the upstream riparian not exercising their rights to water from the river. In return, the income generated from the delta is used to benefit the region by embarking on transfer of tourism initiatives and development projects. The upstream counties would in this way be compensated for not using their share of the water, on the assumption that the use of downstream brings a higher overall return to the water used. The countries of the region bear no resemblance to the shapes of the river basins, with borders drawn by colonial powers to define spheres of influence. Frequently, due to the relatively small size (width) of the rivers, there was a high level of interaction between communities on opposite banks. People have a shared history, culture, and traditions often with relatives living on the other side of the river. Postcolonial Africa has upheld these borders, casting in stone the division of these once-linked groups. The net result is that people living on the edge of many of these rivers now fall under the influence of an administrative government frequently very far away, yet have to compete or cooperate with people living opposite them, with whom they have more in common. People in the Southern African region frequently feel alienated by the concept of the state—identifying little with the values and aspirations espoused by politicians and government officials. In fact, nation building is a core strategic need for many of the Southern African states. Allegiance, bonds, and responsibility tend to be strongest at the local level, with management based on networks of trust, operating within and between communities according to Earle and Turton [8]. In this way, it is possible for cooperation over shared water resources to be focused around river basins. Communities dependent on the resource may be separated by nationality, yet they are bound by the water they share. The hydropolitical vulnerability to climatic and population pressures of such communities can be reduced by developing their social resources and promoting their cooperation with communities upstream and downstream of them.

24.6.5 Challenges

The challenge faced by the Southern African Development Community (SADC) is how to manage water at the regional level for maximum benefit to all of its member states. Despite the significant progress made so far, there are several strategic challenges that require further work. The water scarcity rampant in some parts of the region and competing developmental requirements between member states may result in disputes and tension over water. Other challenges arise from a variety of facts including the fact that rainfall in the SADC region is highly variable, with the resulting impact on reliability and disaster associated with droughts; the available water resources are unevenly distributed across the region and water availability and demand are not matched.

24.6.5.1 Southern Africa's Water for Economic Integration

Water markets: Water shortages due to drought, urban population growth, and climate change are occurring throughout the world. The application of market forces will be an effective way to achieve a balance between supply and demand, to facilitate efficiency by disclosing noncompetitive and inefficient water users, and to stimulate the use of technical and procedural innovations to maximize water use efficiency. While increasing conservation and recycling will result in more efficient use of water, interbasin transfers will continue to play a large role in assuring a reliable supply of water. It is important to note that use of water involves an unusually complex mix of price-responsive and nonprice-responsive social values. The interrelations among water uses, in-stream public trust needs, and nonconsumptive uses such as flood control, power generation, and recreation must all be considered.

24.6.5.2 Socioeconomic Impacts in the Source Basin

A different challenge is to minimize or mitigate the socioeconomic impacts to a feasible extent. It is estimated that if the entire transfer were based on fallowing of farmlands, 1400 jobs would be lost. Fallowing would not only increase the unemployment rate but would also adversely affect the local government by reducing its tax base and increasing its administrative costs. Economic impacts will vary depending on the quality of lands fallowed and the crop types being replaced. The state is required to study the nature and extent of any impacts of land fallowing and the extent to which funds gained from the transfer do not mitigate for these costs. Additional mitigation funding requirements may be imposed if the studies indicate that they are necessary.

24.7 Summary and Conclusions

Climate variability is a key determinant of Southern Africa's ecological dynamics and environmental security. However, it is not possible to predict what impact the introduction of global climate change will have on the levels of cooperation, conflict, vulnerability, and reservation of water resources in the region. Interbasin transfers of water are responsible for more than 50% of the GGP in seven of South Africa's nine provinces. There is simply no more water available in the Limpopo and Orange River basins. Alternatives need to be found as a matter of strategic importance. Data imbalances increase power disparities within river basins, acting as fundamental drivers of conflict potentials. The focus of cooperation should be on sharing the benefits of the water resource, rather than a strict adherence to sharing the water itself. Ultimately, the states of South Africa are in real need for environmental and legal controls to protect the public resources and source water basin.

Author

Samir Anwar Al-Gamal completed his PhD from Cairo University, Egypt. He completed his first post-doctor fellowship from Paris-6 University, France, and his second fellowship from Stockholm University, Sweden, and masters in hydrogeology jointly from King Abel-Aziz University, Jeddah, and Istanbul Technical University. He has completed his BSc in geology at Ain Shams University, Egypt. He joined the University of Engineering and Technology (Taxila) as a foreign faculty professor, Department of Civil and Environmental Engineering, Pakistan. Before joining Taxila University, he was seconded to Sahara and Sahel Observatory (OSS) based in Tunisia as an advisor in water resources. Before joining OSS, he was the chairman of Siting and Environment Department and Nuclear Safety Division Director in Egyptian Atomic Energy Authority. He is currently a member of the editorial board of the following international peer-reviewed journals: *Journal of Hydrology*, *Journal of Water Resources and Environmental Engineering*, *African Journal for Geosciences*, and *Journal of Scientific Research and Review*. He is the author of over 50 journal articles and has written 18 reports, 5 book chapters, and presented over 30 conference papers. Prof. Dr. Samir Al-Gamal's primary research areas include climate changes impact on water resources in Africa, quantifying water dynamics using environmental isotope tracers, and integrating water resource assessments, currently focusing on transboundary aquifers in Africa (39 aquifers). He has over 30 years' experience in water research.

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25

Drought Management Planning Resources for Water Suppliers in Pakistan

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Abstract The chapter discusses drought management planning resources for water suppliers in the drought-affected areas of Pakistan, particularly in Sind, lower Punjab, and Balochistan. Due to its geographical extent, the intensity of rainfall in Pakistan is variable at different parts and seasons. Some areas of the country, in each season, remain drastically dry and are vulnerable to drought. If subsequent seasons also fail to generate significant precipitation, the drought conditions are then sure to take the regions in grip. Such conditions are often seen affecting the country, specifically the southern half of the country. The southern latitudes of Pakistan receive precipitation less than 10 in. and have remained dry for centuries. Each year, a partial drought prevails over the areas, which changes into severe drought every 5 years. The population of the arid regions is under stress for water resources and needs proper water resources management to save the flora and fauna in the area.

In view of the fact that the country mostly consists of arid, semiarid, and even hyperarid regions, the susceptibility of different regions to become drought-stricken is always very high. Drought is a natural event and the risk associated with drought is a product of both the region's exposure and the vulnerability of society to the event. For its management and prevention of water resources, we need to explore the drought-vulnerable areas, causes, short-term and long-term adaptation strategies to cope with the problem, and how to promote the existing water supply methods for the provision of water resources in the area.

An attempt is made to cover these aspects in this chapter, which would help promote further investigations in the drought management planning resources for water suppliers in the context of historical as well as modern strategies in the arid regions of Pakistan.

25.1 Introduction

The term drought means different things to different people. To the meteorologist, a drought is primarily a precipitation deficit, which is the most readily measured climatological parameter. The meteorological definitions of drought severity are of two types: First, they may be based on the absolute threshold, expressed either as a limiting total of precipitation or as a minimum sequence of days with no precipitation. Second, there are relative measures—less than a certain percentage of the "normal" annual or seasonal precipitation totals, or an amount that represents some lower range of frequency distribution. From a biological standpoint, a drought denotes the aggregate effect of persistent anomalies of precipitation, evaporation, soil moisture, and runoff acting on vegetation communities.

A drought is the deficit that results when the soil moisture is insufficient to meet the demands of the potential evapotranspiration. Three classes of drought may be differentiated: first, the permanent drought, which is associated with arid climates; the second is the seasonal drought, which occurs in climates with distinct annual periods of dry weather; and the third is the drought due to the precipitation variability.

It is concluded from the literature cited that the term drought is defined as a prolonged continuous period of dry weather and deficiency of water for plants' protection. It may be divided into the absolute drought, the partial drought, the permanent drought, and the dry spell. An absolute drought is defined as a period of at least 15 consecutive days with rainfall less than 0.25 mm on each day. A partial drought is a period of 29 consecutive days on some of which slight rain may fall, but during which the average rainfall does not exceed 0.25 mm (0.01 in.). In spite of this, a permanent drought constitutes a prolonged period of rainfall deficiency, which is mainly associated with dry climates. Furthermore, the dry spell of a place is a period of 14 days without measurable precipitation.

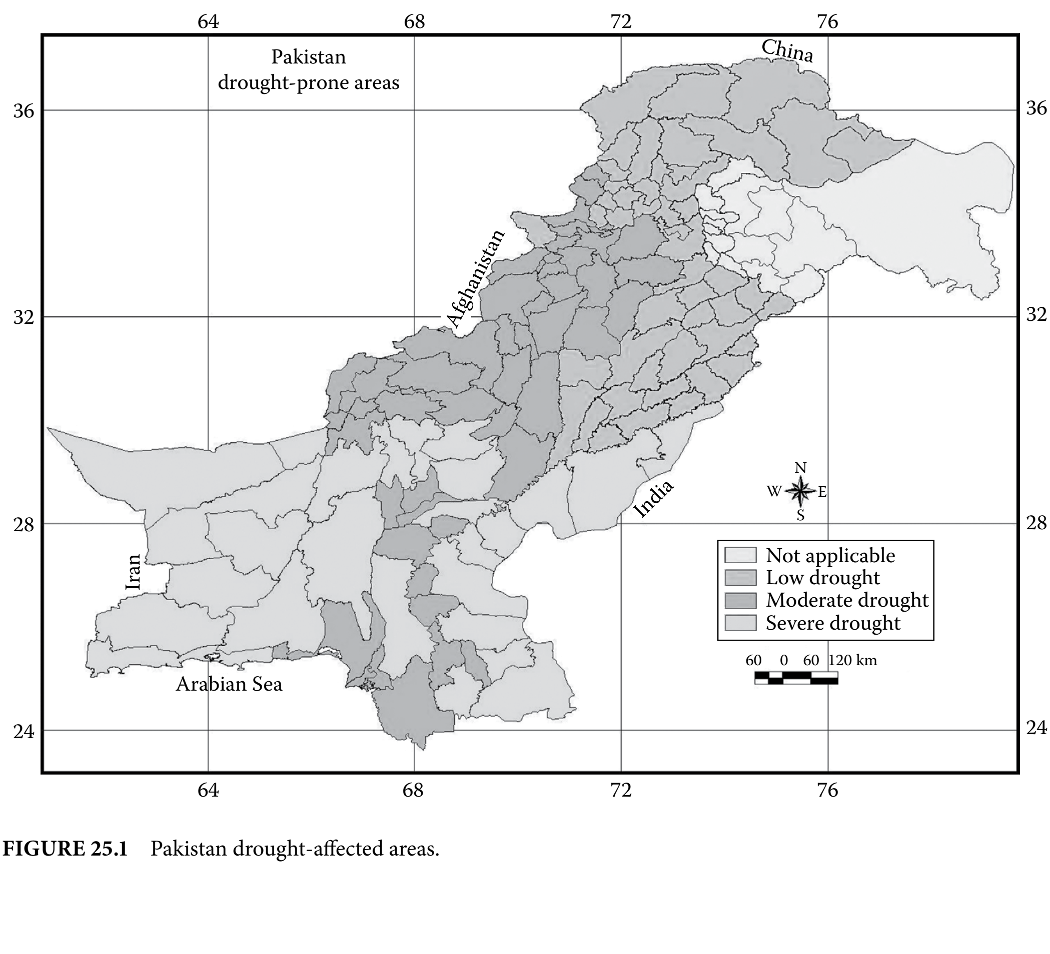


FIGURE 25.1 Pakistan drought-affected areas.

The history of drought in Indo-Pakistan is very old. The land of Southeastern Asia has undergone 19 major famines in the last one hundred years. Of these, the worst famines were in 1877, 1899, and 1918, when, in each case, more than 60% of the population was ravaged.

The arid zone of Indo-Pakistan covers about 750,000 km^2. In the north, it takes in the southeastern part of Punjab (Cholistan desert), on the east it is bounded by the Aravali mountains, in the south it reaches the Arabian coast, and in the west it extends to the western border of Balochistan. All Rajasthan particularly west of the Aravali mountains, the southwestern tip (India) and the southeastern tip of Punjab (Pakistan) and most of the Khyber Pukhtunkhwa province.

The current work deals with water resource planning for the drought-affected areas of Pakistan. Pakistan extends approximately northeast to southwest from latitude 24°N to 37°N and longitude 60°E to 75°E (Figure 25.1). Lofty Himalayas form its northern frontiers with the semiarid Hindukush and Sulaiman mountains in the west. The Tropic of Cancer runs through the southern part of the country. In the south, along the coast of Arabian Sea, is a narrow arid marine belt. The rest of Pakistan is arid excluding a narrow belt of submountains and mountainous Punjab and upper Khyber Pukhtunkhwa, which is subhumid. These factors give a typical climatic personality to Pakistan in Southeast Asia [16].

According to the Intergovernmental Panel on Climate Change (IPCC), Fourth Report in 2007: "The recent climate change has increased summer drying and associated incidence of drought in a few areas (likely). In some regions, such as parts of Asia and Africa, the frequency and intensity of droughts have been observed to increase in recent decades."

Keeping in view this discussion, a study has been devised to elaborate different options for drought management planning resources for water suppliers. The proposed strategy will not only be applicable for the drought-affected areas of Pakistan but will also be beneficial at the international level.

25.2 Methodology

The specific purpose of the study is to find ways for the drought management planning of resources for water suppliers in the drought-affected areas of Pakistan. The main questions are: what is drought, how it impacts the water resources in the arid areas, and what planning is required to cope with the problem. The general hypothesis is that a drought affects the water resources of the arid regions and proper planning is required to cope with the situation. The present work is based on the information collected from the literature cited and personal interviews. The results are compiled in the form of discussions, conclusions, and recommendations.

25.3 Findings and Discussions

Before discussing the recent approaches of water management and harvesting, it is necessary to examine the historical methods of water management in the drought-affected areas of Pakistan.

25.3.1 Historical Water Management (Indus Civilization)

The Indus civilization is best known through the excavation of Mohenjo-daro, which literally means "The mound of the dead," located in the Sind province in the drought-affected area of Pakistan, about 40 km from Larkana town, and another site 209 km due north of Hyderabad city [9]. A similar and larger ruin, Harappa, is located some 644 km northeast of Mohenjo-daro in the Punjab province, and in this general area between Mohenjo-daro and Harappa, there are numerous mounds indicating other cities of the same Indus civilization, and in addition there are mounds of an even earlier and distinct Amri Culture. The third site Lothal (dockyard of the Indus Valley Civilization) was discovered some 60 years ago, located about 7 km away from the Ahmedabad–Bhavnagar highway, India [1]. Most of the Indus Valley Civilization spread over a vast area of lower Punjab, Sind, and the coastal area of Balochistan and covered the drought-affected areas of Thar, Cholistan, Nara, and Kharan deserts.

FIGURE 25.2 Great Bath at Mohenjo-daro. (From Kenoyer, J.M., *Mohenjo-Daro: An Ancient Indus Valley Metropolis*, University of Wisconsin, Madison, WI, 1998, Online, http://www.harappa.com/indus3/kenoyer.html.)

25.3.1.1 The Great Bath

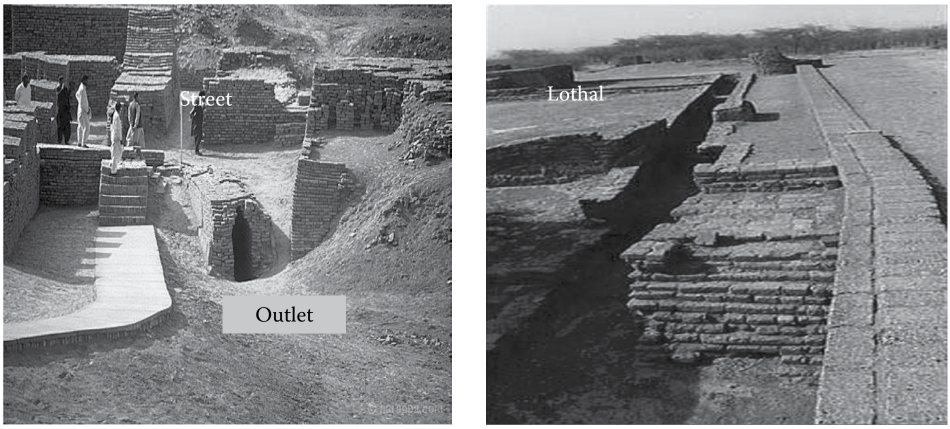
The "Great Bath" is without doubt the earliest public water tank in the ancient world, located at the archeological site of Mohenjo-daro, a drought-affected area of the Sind province. The tank itself measures approximately 12 m north–south and 7 m wide, with a maximum depth of 2.4 m [7]. Two wide staircases lead down into the tank from the north and south with small treads. At the foot of the stairs is a small ledge with a brick edging that extends sockets at the edges of the stairs that are thought to have held wooden planks for the entire width of the pool. People coming down the stairs could move along this ledge without actually stepping into the pool itself (Figure 25.2).

The floor of the tank is watertight due to finely fitted bricks laid on the edge with gypsum plaster, and the sidewalls were constructed in a similar manner. To make the tank even more watertight, a thick layer of bitumen (natural tar) was laid along the sides of the tank and presumably also beneath the floor. Brick colonnades were discovered on the eastern, northern, and southern edges. The preserved columns have stepped edges that may have held wooden screens or window frames. Two large doors lead into the complex from the south and other access was from the north and east. A series of rooms are located along the eastern edge of the building and in one room is a well that may have supplied some of the water needed to fill the tank. Rainwater also may have been collected for this purpose, but no inlet drains have been found [26].

The principal community bath was a structure of considerable size, conforming somewhat to our ideas of a swimming pool, though perhaps being used rather as a place for religious ceremonials than for either mere pleasure or for only the cleansing of the body. The structural features of the pool indicate an excellent ability in construction, considering the building materials available at that time and place. For example, waterproofing was accomplished by a membrane or coating of asphaltum between the inner and outer walls of the pool or tank [9].

25.3.1.2 Water Treatment

The Indus Valley Civilization was known for its water management. Most of the excavations have been found around the areas of the cities of Harappa, Mohenjo-daro, and Dholavira. They were known for their



(a) (b)

FIGURE 25.3 (a) Great Bath outlet Mohenjo-daro and (b) Lothal sanitation. (From Kenoyer, J.M., *Mohenjo-Daro: An Ancient Indus Valley Metropolis*, University of Wisconsin, Madison, WI, 1998, Online, http://www.harappa.com/indus3/kenoyer.html.)

obsession with water [12]. They prayed to the rivers every day and gave them a divine status. They had well-constructed wells, tanks, public baths, a wide drinking system, and a city sewage system. Each city had two regions—a higher ground, which contained the "Citadel," was the main administrative area, and the lower city, where the houses were situated. All the important areas were situated on the higher ground. The baths and wells were situated there, which suggests the importance they were given [22].

The inhabitants of Mohenjo-daro were masters in constructing wells. It is estimated that about 700 wells have been built within their city, an average of one well for every third house. They were constructed with tapering bricks that were strong enough to last for centuries [4]. The cities too had strong walls to resist damages due to floods. One reason for this large number is that Mohenjo-daro received less winter rain and was situated further from the Indus River than the other prominent cities. Hence, it was necessary to collect and store water for various purposes (Figure 25.3).

25.3.1.3 Baths and Wells

One of the best-known excavations is the Great Bath of Mohenjo-daro, which has been discussed. In addition to wells, archaeologists have also found remains of giant reservoirs for water storage. Reservoirs were situated around the metropolis, which was fortified with stonewalls. The Archaeological Survey of India has revealed that one third of the area of the city of Dholavira in the Rann of Kutch was devoted to collection and distribution of freshwater. The city was situated on a slope between two streams. At the point where one of the streams meets the city's walls, people carved a large reservoir out of a rock. This was connected to a network of small and big reservoirs that distributed water to the entire city all year round. All the reservoirs together could hold about 248,480 m^3 of water. Such was the importance they gave for water storage. According to Gray [9], many of the houses in the Indus civilization had their individual wells within buildings. These wells were usually circular in plan, though at times oval, and had copings of stones or bricks at the floor level, and brick lining for a moderate depth below the surface (Figure 25.4). In a few instances, the street drains ran rather too close to the wells, and it is possible that some contamination of the well had occurred. But in most cases, the wells were located at adequate distances from the drains.

Generally, the Mohenjo-daro ruins present a picture of a community in which both personal and community cleanliness was quite effectively practiced, and the water supply reasonably safeguarded from contamination as a rule. Practically every house in Mohenjo-daro had its bathroom always placed on the

FIGURE 25.4 Different types of wells and water tanks in the Indus Civilization. (a) Oval well, (b) pipal leaf form well, (c) underground watertank, (d) watertank, (e) watertank, and (f) underground well. (From Kenoyer, J.M., *Mohenjo-Daro: An Ancient Indus Valley Metropolis*, University of Wisconsin, Madison, WI, 1998, Online, http://www.harappa.com/indus3/kenoyer.html.)

street side of the building for the convenient disposal of wastewater into the street drains. Where latrines have been found in the houses, they were placed on the street wall for the same reason. Ablution places were set immediately adjacent to the latrines, thus conforming to one of the most modern of sanitary maxims. Where baths and latrines were located on the upper floor, they were drained usually by vertical terracotta pipes with closely fitting spigot joints, set in the building wall.

In the bathrooms, people stood on a brick "shower tray" and tipped water over themselves from a jar. The clean water came from a well. The dirty water was drained through a pipe out through the wall into the drain in the street [19]. These ancient terracotta pipes, still sound after nearly 5000 years, are the precursors of our modern verified clay spigot-and-socket sewer pipe and are an excellent guarantee of the durability of this material.

25.3.1.4 Drainage System

The Indus civilization had an elaborate sanitary and drainage system, the hallmark of ancient Indus cities. The authorities maintained a highly efficient drainage system. Each and every house had a connection with the main drain. These even had inspection holes for maintenance. The conduits to the main drains ran through the middle of the streets below the pavement level and were covered with flat stones and sturdy tile bricks. The covered drain was connected to the larger sewerage outlets, which finally led the dirty water outside the populated areas. The urban plan found in these cities included the world's first urban sanitation system. The elaborate brick-linked drainage system for the removal of rainwater is of unparalleled engineering skill [25].

With such an extensive domestic water storage system, the associated problem that arises is that of drainage. Town planners of Mohenjo-daro had built the world's first known main drainage system. It was a central system that connected every household in the city (Figure 25.3). Every house had a drinking water well with a private bathroom. Earthenware waste pipes carried sewage from each home into covered channels that ran along the centers of the city's main streets into the nearby agricultural fields, rivers, or streams. The drains took waste from kitchens, bathrooms, and indoor toilets. The main drains even had movable stone slabs as inspection points. The houses had excellent plumbing facilities for provision of water [25]. Toilets had brick seats. The toilet was flushed with water from jars. The waste flowed out through clay pipes into a drain in the street. Waste was carried away along the drains to "soak pits" (cesspits). Cleaners dug out the pit and took the waste away. They also took away rubbish from bins on the side of houses. Each street and lane had one or two drainage channels, with brick or stone covers, which could be lifted to remove obstructions in the drains. The drains usually ranged from 46 to 61 cm below the street level and varied in dimensions from 30.50 cm deep and 23.00 cm wide [9]. When the drain could not be covered by flat bricks or stone slabs, the roof of the drain was corbeled.

25.3.1.5 Irrigation System

The Indus Valley Civilization in Pakistan (from *ca.* 2600 BC) also had an early canal irrigation system. Large-scale agriculture was practiced and an extensive network of canals was used for the purpose of irrigation. Sophisticated irrigation and storage systems were developed, including the reservoirs built at Girnar in *ca.* 3000 BC [27]. Besides, some of the toys of the Indus Valley Civilization indicate that there was a proper system of water supply into different houses and places (Figure 25.5). Mostly, women had the

FIGURE 25.5 Figurine showing water supply in Mohenjo-daro. (From Kenoyer, J.M., *Mohenjo-Daro: An Ancient Indus Valley Metropolis*, University of Wisconsin, Madison, WI, 1998, Online, http://www.harappa.com/indus3/kenoyer.html.)

responsibility to supply water into different places. Farmers made good use of water from the rivers. They sowed seeds after the rivers had flooded the fields, as floodwater made the soil rich. They planted different crops for winter (which was mild and wet) and summer (which was hot and dry). They were probably the first farmers to take water from underground wells. They may have used river water to irrigate their fields. Their main cultivation products, amongst others, were peas, sesame seed, and cotton. They also domesticated wild animals in order to use them for harvesting their farms [18].

25.3.1.6 Rainwater Harvesting and Storage System

The Indus Valley Civilization that flourished along the banks of the river Indus and other parts of western and northern India about 5000 years ago had one of the most sophisticated urban water supply and sewage systems in the world. The fact that the people were well acquainted with hygiene can be seen from the covered drains running beneath the streets of the ruins at both Mohenjo-daro and Harappa. Another very good example is the well-planned city of Dholavira, on Khadir Bet, a low plateau in the Rann in Gujarat. One of the oldest water harvesting systems is found about 130 km from Pune along Naneghat in the Western Ghats [14]. A large number of tanks were cut in the rocks to provide drinking water to tradesmen who used to travel along this ancient trade route. Each fort in the area had its own water harvesting and storage system in the form of rock-cut cisterns, ponds, tanks, and wells that are still in use today. A large number of forts, like Raigad, had tanks that supplied water (Figure 25.6).

"The kind of efficient system of Harappans of Dholavira, developed for conservation, harvesting and storage of water speaks eloquently about their advanced hydraulic engineering, given the state of technology" [28]. One of the unique features of Dholavira is the sophisticated water conservation system of channels and reservoirs, the earliest found anywhere in the world and completely built out of stone, of which three are exposed. Dholavira had massive reservoirs. They were used for storing the freshwater brought by rains or to store the water diverted from two nearby rivulets. This clearly came in the wake of the desert climate and conditions of Kutch, where several years may pass without rainfall. A seasonal stream, which runs in north–south direction of the site was dammed at several points to collect water (Figure 25.7). The Great Bath at Mohenjo-daro is also an evidence of the water conservation and storage system [29].

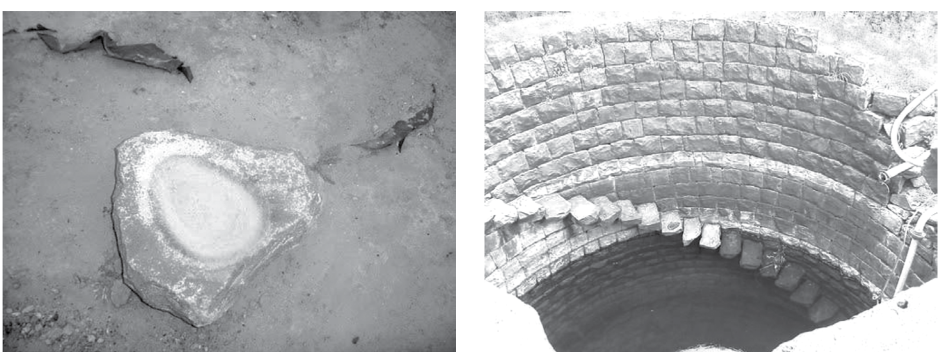
The inhabitants of Dholavira created 16 or more reservoirs of varying sizes. Some of these took advantage of the slope of the ground within the large settlement, a drop of 13 m from the northeast to northwest. Other reservoirs were excavated, some into living rock. A recent work has revealed two large reservoirs, one to the east of the castle and one to its south, near the annexe, shown in Figure 25.8 [30].

FIGURE 25.6 Water tank at Mohenjo-daro. (From Kenoyer, J.M., *Mohenjo-Daro: An Ancient Indus Valley Metropolis*, University of Wisconsin, Madison, WI, 1998, Online, http://www.harappa.com/indus3/kenoyer.html.)

FIGURE 25.7 Hydraulic engineering Indus Civilization at Dholavira, Rann at Gujrat. (From Wales, J., Dholavira, Wikipedia, the free encyclopedia, 2010, http://en.wikipedia.org/wiki/Dholavira#cite_note-frontline-1#cite_note-frontline-1, online.)

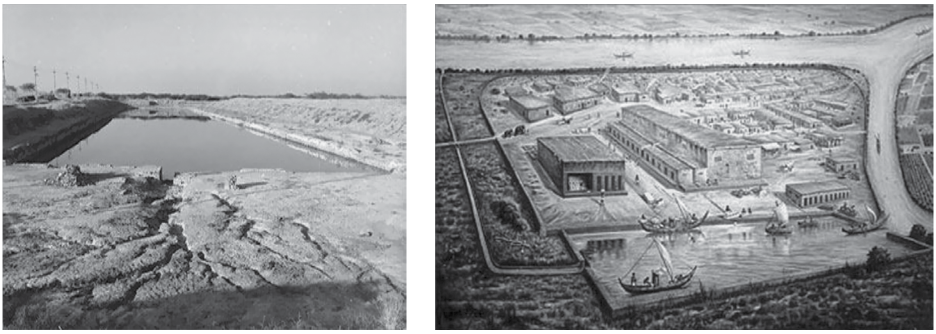
Reservoirs are cut through stones vertically. They are about 7 m deep and 79 m long. Reservoirs skirted the city, while the citadels and baths are centrally located on raised ground. A large well with a stone cut through to connect the drain meant for conducting water to a storage tank has also been found. Bathing tanks had steps descending inward as in Figure 25.8.

A large number of tanks (Figure 25.8) were cut in the rocks to provide drinking water to tradesmen who used to travel along the trade route. Each fort in the area had its own water harvesting and storage system in the form of rock-cut cisterns, ponds, tanks, and wells that are still in use today. A large number of forts, like Raigad, had tanks that supplied water for domestic use [30].



(a) (b)

FIGURE 25.8 (a) Storm water storage in rock tank and (b) dry well at Dholavira and Lothal. (From Wales, J., Dholavira, Wikipedia, the free encyclopedia, 2010, http://en.wikipedia.org/wiki/Dholavira#cite_note-frontline-1#cite_note-frontline-1, online.)



(a) (b)

FIGURE 25.9 Dockyards at (a) Lothal and (b) Courtes. (From Kenoyer, J.M., *Mohenjo-Daro: An Ancient Indus Valley Metropolis*, University of Wisconsin, Madison, WI, 1998, Online, http://www.harappa.com/indus3/kenoyer.html.)

25.3.1.7 Dockyard at Lothal

The dominant site at Lothal is the massive dockyard, which has helped make this place so important to international archaeology. Spanning an area of 37 m from east to west and nearly 22 m from north to south, by some the dock is said to be the greatest work of maritime architecture before the birth of Christ [21]. To be sure, not all archaeologists are convinced that the structure was used as a dockyard and some prefer to refer to it as a large tank that may have been a reservoir (Figure 25.9).

It was excavated beside the river Sabarmati, which has since changed course. The structure's design shows a thorough study of tides, hydraulics, and the effect of seawater on bricks. Ships could have entered into the northern end of the dock through an inlet channel connected to an estuary of the Sabarmati during high tide. The lock gates could then have been closed so the water level would rise sufficiently for them to float (Figure 25.9).

An inlet channel 1.7 m above the bottom level of the 4.26 m deep tank allowed excess water to escape. Other inlets prevented siltation of the tanks and erosion of the banks. After a ship would have unloaded its cargo, the gates would have opened and allowed it to return to the Arabian Sea waters in the Gulf of Cambay [21].

Archaeological finds from the excavations testify to trade with ancient Egypt and Mesopotamia. The hydraulic knowledge of the ancient Harappans can be judged by the fact that boats could dock at Lothal in the 1850s. In 1942, timber was brought from Baruch to nearby Sagarwala. It is said that then the dockyard could hold 30 ships of 60 tons each or 60 ships of 30 tons each. This would be comparable to the modern docks at Vishakapatnam [21].

A long wharf connected the dockyard to the main warehouse, which was located on a plinth some 3.5 m above the ground. The first concern of the Harappan engineers might have been to ensure against floods and tides (which may have been their undoing at Mohenjo-daro and Harappa).

25.3.2 Historical Drought in Pakistan and India

Pakistan frequently experiences droughts in the arid regions. The Punjab province underwent the worst droughts in 1899, 1920, and 1935. The Khyber Pakhtunkhwa province experienced such droughts in 1902 and 1951, while Sind had its worst droughts in 1871, 1881, 1899, 1931, 1947, and 1999 [17]. The most severe droughts at the national scale were perhaps the most recent, which occurred in 1999–2000, prolonging up to 2002 in certain areas (Table 25.1). The precipitation was erratic and river flows had dropped. The water in the Tarbela dam reached dead level in late February or early March almost every year. The recent drought (1999–2002) has also exposed the vulnerability of the Indus basin irrigation system and environmental issues in deltaic areas.

TABLE 25.1 Historical Droughts in India and Pakistan, 1802–2002, by Kulshreshta and Sikka

Class Range	Drought Years	No. of Years
1801–1825	1801, 1804, 1808, 1812, 1819, 1825	6
1826–1850	1832, 1833, 1837	3
1851–1875	1853, 1860, 1862, 1866, 1868, 1873	6
1876–1900	1877, 1891, 1899	3
1901–1925	1901, 1904, 1905, 1907, 1911, 1913, 1915, 1918, 1920, 1925	10
1926–1950	1939, 1941	2
1951–1975	1951, 1965, 1968, 1972, 1974	6
1976–2002	1979, 1982, 1985, 1987, 2002	5
1801–2002	Sum	41

Source: Kulshreshta, S.M. and Sikka, D.R., Monsoon and drought in India: Long term trends and policy choices, *National Workshop on Drought Management*, New Delhi, India, 1989, p. 25.

Although, the physical causes of drought are not fully understood, however, several partial explanations of droughts in the arid region of Pakistan have been put forward based on theoretical grounds as well as on the past synoptic situations related to monsoon failures. Among the major factors cited are, "weaker maridinal pressure gradient, larger northward shifts of the monsoon, smaller frequencies of depressions and shorter westward extent of depressions tracks, shift in the western depressions towards northwest, deforestation, soil degradation, increase in temperature and decrease in precipitation [17]."

The situation is particularly serious in areas where groundwater is either deep or brackish and no surface-water resources are available. Other factors that intensified the adverse impact of droughts include overexploitation of groundwater in violation of groundwater regulations, deforestation, depletion of grazing pastures due to lack of management, poor farm water management, and lack of controlled cropping patterns. These factors need further research to elaborate each and every aspect in view of how to reduce the impact of the drought in the arid region of Pakistan and to plan for the water supplies in the drought-affected areas.

25.3.3 Irrigation Systems

Irrigation is a very old tradition in Pakistan. Beginning with simple lift irrigation, today, Pakistan has developed one of the most interacted and complex systems of canal irrigation in the world. In Pakistan, 75% of the total cropped area is under irrigation, while the rest depends on rains.

Lift irrigation is one of the earliest methods of irrigation practices in Pakistan. In this method, water is lifted by hand in a bucket attached to a rope. This could be done only from shallow wells and ditches. It requires a considerable amount of labor and therefore, only a small area could be irrigated by this system. Karez is another method of irrigation confined to Balochistan. Generally, it is a water tunnel or it is looked upon as a narrow canal. This system of water irrigation is mostly used in desert areas, where the underground water surface is very deep, especially in Balochistan and south-eastern Indus plains.

Another irrigation system is the canal system. Normally, the canals were narrow irrigation channels diverted from small shallow streams. They commanded a small area. Such small diversions are still in use in Balochistan and other parts of Pakistan. The small dams are made across narrow and shallow streams and the stored water used for irrigation system. The second type is digging of canals that take off from large rivers. It may be inundation canals, which receive water when the level of the river is raised by flood. The third is perennial canals, which have taken off from weirs and barrages to supply water throughout the year. The fourth one is the link canal, which are the main carriers of water from the western rivers to the eastern rivers and from the rivers into canals. These three types of canal systems exist everywhere in Pakistan and play a vital role in the irrigation system of the country.

25.3.4 Planning for Water Resources in Drought-Affected Areas

This section discusses the short- and long-term planning for water resources in drought-affected areas.

25.3.4.1 Short-Term Planning

The various factors responsible for a short-term basis of combating drought are as follows:

- To provide relief fund to drought-affected areas immediately.
- To ensure the availability of water to the inhabitants of the drought-affected areas. To send various teams of doctors, engineers, social workers, etc. to the drought-affected areas and to control the mortality rate of humans as well as livestock.
- To provide transportation facilities to people who have no source to reach the relief camps.
- Instead of migration to cities, it is necessary to restrict the drought-affected people to various camps and save the urban areas and towns from human stress.
- To decrease the ratio of rural–urban migration, it is necessary to provide relief to people in their own villages or towns.
- To decrease the mortality rate and migration of livestock from the drought-affected areas, it is necessary to recharge water in the ponds or water tanks in the grazing lands.
- To provide shelter and food for infants of the immigrants of the drought-affected areas.
- For the increase in water tables, it is necessary to recharge water tables using railways, vehicles (artificial recharging), and divert canals immediately.
- Forecast of monsoon and western disturbances as early as possible to enable farmers to be prepared for good, normal, and bad seasons.
- Communication system in the drought-affected areas must be improved.
- Availability of resources such as credits, fertilizers, pesticides, and power should be ensured for increasing crop production.
- Proper assurance to the farmers as well as to the inhabitants of the drylands in the year when the western disturbances occur and monsoon fails.
- For the change in the natural environment, artificial rainfall is needed to increase atmospheric moisture.
- It is required to provide insurance facilities for the livestock, crops, health, and shelters to the inhabitants of the drought-affected areas.

25.3.4.2 Long-Term Planning

The drought-related impacts can only be reduced through proper planning. A number of measures are needed for the same. Communities in the arid region themselves are the key in adaptation to drought as they are the ones who know and are aware of the changes that take place in their environment, and how these impact them, whether it concerns water supply or other sources of livelihood. Nevertheless, the government's assistance is also indispensable as communities in the arid region are mostly vulnerable with a lack of resources.

25.3.4.3 Expansion in Irrigation Systems

Being an agriculture economy, Pakistan is extraordinarily dependent on its water infrastructure, and it has invested in it massively. Due to the time factor, much of the infrastructure in Pakistan is collapsing. This is true even for some of the major barrages, which serve millions of hectares and where a failure would be disastrous.

Due to the recent drought and precipitation deficit, aridity has increased and there is a need of improvement in irrigation requirements. The increase in population and irrigation water demand would affect the water availability in the lower Punjab and Sind provinces. Therefore, to extend the irrigation facilities to the rainfed areas is needed. The main factors to cope with the problem of drought and expansion of irrigation systems in the arid regions are as follows:

- The surface water supplies from the adjacent watersheds can be managed for diversion to agriculture lands if flows are perennial. In case flows are nonperennial, the runoff can be stored in reservoirs and dams and then regulated to provide irrigation and settlements. There is a great potential of storing runoff areas within or outside the Indus basin in lower Punjab and Balochistan, which will also reduce flood hazards.
- The increase in irrigation water demand would force the farmers to start using low quality of water in fragile environments that will negatively affect the productivity of crops and also cause different diseases.
- To invest more in the irrigation facilities, especially in rainfed areas or drought-affected areas already facing a dearth of surface water because of aridity and climate fluctuation.
- The farmers have turned to use groundwater to maintain crop productivity, which is adversely affecting the water table. The introduction of irrigation facilities in the arid region will not only help to increase the crop productivity but will also increase the recharging capacity of water tables.
- The governments should develop and improve the canal irrigation system along with the other water resources like tubewells, *Karez*, and wells, etc.
- The governments are needed to invest more in the development of rainwater or floodwater irrigation systems. This will also decrease the process of desertification in the area. The airborne precipitation (artificial rain) is more suitable for the areas located closer to the Arabian Sea for farms' cultivation. Private sectors should also be invited to invest in the irrigation projects of the country for the improvement and utilization of floodwater for the development of agriculture in arid regions.

25.3.4.4 Planning for Water Sectors

The adaptation strategy of any issue in the future and for the vital issue of water resources planning, development, and management in particular has to be sustainable, technologically advanced, and visionary. Water resources planning, development, and management are ecologically, technologically, and sociologically complex. Adjustment to drought impacts will only be effective if these complexities are properly understood. Water planning should concentrate on the dynamics of the water resource system. Impacts on flood, deposition, and weather represent high priorities for additional investigation and planning. Climate-imposed considerations can be incorporated within medium- and long-term water investment planning and projects appraisals. Given the importance of the Indus River, it would be advisable to broaden the scope of water planning to address the long-term impacts of climate change in conjunction with pressing water problems in the arid region.

The water sector is more vulnerable to drought and is counted as a major environmental problem. Adaptation to the adverse effects of climate change on surface and subsurface hydrology, therefore, will be a part of the overall comprehensive strategy to overcome the current as well as future environmental changes.

Under almost all circumstances the water sector shows that the system could not meet the entire demand of the agriculture sector as well as domestic use in the future. Necessary measures, therefore, would be required to overcome the adverse effects or to obtain the benefits of the positive impacts.

The current flow of water and its storage does not fulfill the need of agriculture in the arid region. It is evident from the analysis of the water flow in the Indus system that if extra flow or extra storage is not added to the current capacity then there will be serious water-related crises in the dry years, not only in the arid region but also on the national level. Major changes will take place in the rivers' flows and as a result the economy of the country will suffer and the lives of people in the arid regions will be at risk.

The environment and economy of the arid region is highly dependent on the onset and retreat of monsoons, western disturbances, and water supplies from glaciers and snowmelts. Excessive and inadequate precipitation causes floods and droughts, respectively, and they have damaging effects on the crops in lower Punjab and Sind. The current climate change can cause serious impacts on the monsoons and western disturbances, frequency, and distribution of rain spells, accelerating the melting of glaciers and increasing the frequency of floods and droughts. The major adaptive steps to the ongoing climate change and its impacts on the water sector in the arid region of Pakistan are summarized as follows.

25.3.4.5 Water Management

The most important factor to cope with the impact of climate change on the water sector is the conservation of water resources and building new water reservoirs. Introducing new approaches for planning and management for water resources in the arid region are also required. The following are the key adaptive steps:

1. To overcome the insufficiency of running water caused by climate change, it is necessary to construct additional water reservoirs that will help in the shortage of the water resources in future supplies to different parts of the arid region in Pakistan.
2. Every year, Pakistan faces the problem of flood in the Indus water system, which causes damages to its national economy through the destruction of properties, crops, human residence, and livestock. As there is no facility to store the floodwater in the country and it is therefore recommended to construct bypass reservoirs on the Indus and its tributaries. The major function of these reservoirs will be the storage of floodwater during flood or rainy season and maintaining normal flow in the Indus system. The excess water stored can be added to the normal flow during dry months to fulfill the requirements of the irrigation system in the arid region. This will not only reduce the damages caused by flood every year in Pakistan but will also help to store the extra water and to utilize it for sustainable agriculture.
3. In addition to major water reservoirs, small dams are the second option to overcome the shortage of water and to mitigate the adverse impacts of the climate change especially in the seasonal torrents of Balochistan and the Indus river tributaries.
4. There are a large number of seasonal streams in the arid region, suitable for the storage of small inland dams. They will not only supply water for the people and agriculture needs of the local communities but will also help in recharging of water table. During the wet years or flood, these inland dams will be more suitable for storage of floodwater, while in dry years these will be the only source of the irrigation system and will also help in the domestic use.
5. It is also helpful to store water near residential areas. Digging land near the residential area and storing rainwater as well as domestic used water (polluted) in it are required. This will be more suitable in areas where the water table is deeper and located far from the rivers or canals, especially in the arid region.
6. The government needs to construct bypass canals from the perennial rivers to the inland dams of the arid region. During the high seasonal flow, they have to divert the flow into the inland dams to maintain the water storage capacity in balance. This will provide a base for the water supply to the nearby settlements as well as cultivated areas during the drought period.

25.3.4.6 Policy for Water Management

The government of Pakistan has to improve the policy of water sector management keeping in view the needs of people, agriculture, drought, water table, power resources, national economy, and the current climate change.

25.3.4.7 Early Warning System and Monitoring

Due to the increase in climatic hazards in the arid region, Pakistan has to improve its early warning system and monitoring network to enhance adaptive capacity in vulnerable sectors such as agriculture, natural disasters, water scarcity, and aridity. The following are some factors to cope with impacts of climate change by using the early warning and monitoring system:

- To counter floods and storms, local governments have to develop city flood control and water drainage plans
- To introduce advanced technologies for the monitoring and early warning system for flood, surface water, earthquakes, cyclones, etc.
- To improve the forecasting of weather for agriculture and also to develop new forecasting centers throughout the arid region to control drought, desertification, and water flow

25.3.4.8 Raising of Public Awareness

The public needs to be made aware of the climate issues with respect to the impacts on the local, cultural, and economic environment. Pakistan's strategies to raise public awareness can be summarized as follows:

- All the concerned officials and decision makers should be well aware of the matters related to climate change and their impacts.
- The public should be educated through media about climate change and its impacts on agriculture and water resources. The government has to introduce knowledge about climate change in the curriculum of educational institutions in the country.
- They have to encourage public and private participation, increase the transparency of decision-making processes related to climate change issues, public awareness, social groups, and NGOs have to play active roles in the adaptation of climate change, especially in Balochistan.
- They should strengthen international cooperation on public awareness, especially good practices on climate change education.

25.3.4.9 Improving Research and Development Facilities

There is a need for research and development to meet with the challenge of climate change as it will affect almost all aspects of life in Pakistan. Some of the recommendations to enhance climate-change-related research and development are as follows:

- There is a need to establish dry land research and development funds (DLRDF) on the federal and provincial levels for the control of drought, desertification, and land degradation. It should be run independently by experts and highly specialized people in the field of climate change and desertification.
- Pakistan has to promote scientific and technological research to examine impacts of climate change on the socioeconomic development, analysis of the effectiveness of socioeconomic benefits and costs in response to climate change, surface water, agriculture yield, deforestation, ways of artificial precipitation, waterlogging, and salinity, alternate resources of energy, and advanced technology.
- The federal and local governments have to establish effective incentives, competition mechanisms, and a favorable academic environment for researchers with an international vision and ability to carry out climate change studies; they have to encourage research activities.
- The government should develop a mechanism for the transfer of advanced technologies to the farmers in the arid region.
- They have to identify and develop a variety of seeds for drought-affected areas of Balochistan and Sind.

25.3.4.10 Adaptation to Aridity

The government plans should contain a provision for the implementation of specific actions to detect drought and to mitigate its effects on agriculture production and human lives. Some of the major steps to combat aridity in the arid region of Pakistan are as follows:

- To be aware of the serious deterioration of the natural resources in the surroundings of arid regions and of the need to find ways of improving the standard of living of the locals
- To channelize water resources in different parts of the arid region and to find new areas and irrigation resources for agriculture, locals, and livestock
- To develop agriculture and water resources in accordance with each other for socioeconomic benefits such as jobs and income
- To control the far-reaching change in the land use of the arid region that is caused by the scarcity of water and population growth
- To establish an emergency response plan to save human life and livestock during the drought period in the arid region of Pakistan
- To introduce comprehensive soil management techniques and technologies
- To grow plantation forest, especially the acacia tree, in the surroundings of the arid region to control the expansion of desertification

25.3.4.11 Adaptation Implementation

Implementing adaptation plans and strategies in the arid region is a vital next step for the nations. As highlighted earlier, many plans and strategies have been made and a number of capacity-building steps suggested. Now, it is important to bridge the gap between adaptation assessment and planning and adaptation implementation and to build on knowledge from capacity-building strategies. Adaptation options need to be matched to priority needs both in the context of community-based action and in national and sectoral planning, as well as disaster risk reduction in the arid region. Adaptation plans must be integrated into top-down and bottom-up approaches for planning to enable sustainable development and the efficient use of resources for adaptation in the arid region of Pakistan.

25.3.5 Water Harvesting and Conservation

25.3.5.1 Traditional Methods and Their Extent

Water harvesting is a common practice in the arid areas. Water harvesting captures rainfall and/or runoff and utilizes it for drinking or farming either directly or by storing it in small surface and subsurface reservoirs. The stored water can be used for supplemental irrigation and other consumptive use. In non-irrigated areas, the majority of farmers are still practicing traditional water harvesting systems, which date back to 3000 BC. Traditional water harvesting and conservation practices common in the province of Balochistan and Sind.

25.3.5.1.1 Karezes or Qanats

The karez or qanat is one of the oldest traditional irrigation systems of Balochistan as well as in the neighboring countries—Afghanistan, Iran, Iraq, and the Middle East—which was devised as a means of tapping groundwater supplies using gravity flow. It is a gently sloping tunnel that conveys water from below the water table to the ground surface. It consists of a series of dug wells and tunnels that collect groundwater and discharge it to the command area. Each karez delivers water to the fields of shareholders, who have contributed money and labor for its construction. The modern karez are typically 1–5 km long, but have been as long as 50 km in the past (Figure 25.10). In areas that have very low rainfall and little capacity for storage of surface water, the karez is the primary mechanism for water harvesting and delivery in Balochistan. The residents of an area mark the site where the precipitation drained into an underground

FIGURE 25.10 Karez system at Pishin District, Balochistan, Pakistan.

formation followed by the appearance of water a few kilometers downstream of the command area. The man who organizes villagers to begin and complete the arduous task of building a karez and maintaining it over time holds the office of Sarishtra, the manager of a karez. The Sarishtra holds the land immediately adjacent to the "daylight point" from which the water is discharged (Figure 25.11).

The residents first dug a well down to the groundwater table. This well is called the mother well. In the expected direction of groundwater flow, more wells at a distance of 50–100 m apart are dug to check the following water. Once a karez is established, it can be used for year. A census in 1998 revealed that there were 493 karezes in Balochistan [11]. An average karez can irrigate 10–20 ha. A karez, which yields up to 200 L/s normally, serves a maximum of 200 shareholders.

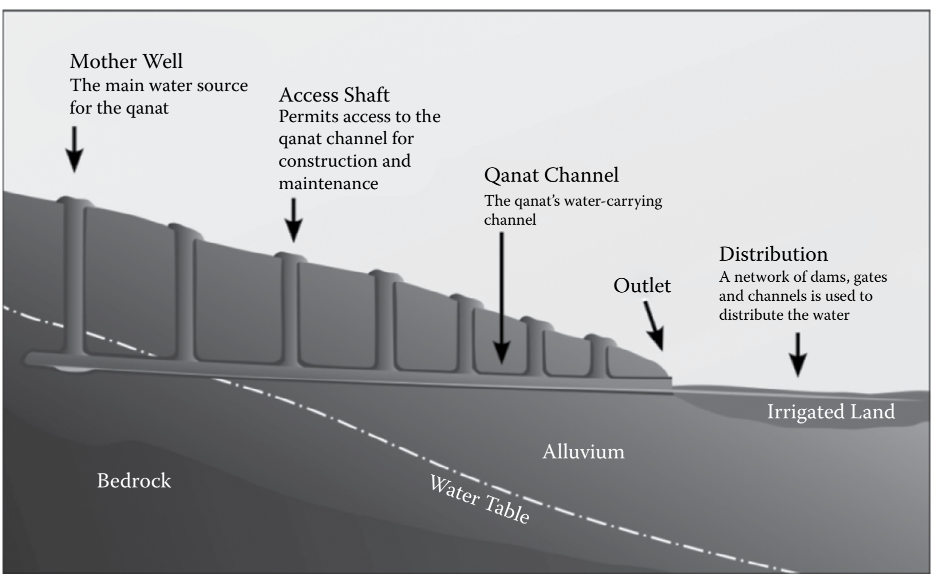


FIGURE 25.11 A schematic cross section of karez system. (From GoP, *A Census of Agriculture*, Islamabad, Pakistan, 2000.)

A karez is a perennial source of water both for domestic and irrigation purposes. In places without a freshwater supply, karez water is used for drinking, washing of clothes, cleaning of utensils, etc. A few decades ago, the agricultural economy was totally dependent upon the supply of karez water. The area irrigated by karezes in Balochistan decreased from 14.2% in 1980 to 7.5% in 2000 [8].

25.3.5.1.2 Sailaba or Rod-Kohi System

The sailaba or rod-kohi system is widely practiced in the Sind and Balochistan provinces in Pakistan, Afghanistan, Iran, and parts of the Middle East. The sailaba cultivation is done by the diversion and spreading of intermittent flows of hill torrents. As the water comes down the hill, it is checked by a series of earthen diversion *bunds* (embankments). To meet their local irrigation needs, small communities have constructed diversion bounds on a number of smaller streams for irrigation. The water thus checked is allowed to seep slowly down into the soil (Figure 25.12). Water rights have been historically determined. Water can only go through the main, predetermined channel. The water is allowed to flow out of the side water channels only when there is excess water. Relatively large fields, each over 3 ha, may be irrigated in this system and deep-rooted crops are usually recommended. The hill-torrent areas in Balochistan are the Kachhi, Zhob-loralai, Makran coastal areas, and the Kharan closed basin, and in Sind, they are the Karachi area, Khirthar range, and Sehwan and Pataro areas [3].

The potential for sailaba in Balochistan is estimated as 1.1 million ha. The historical data, however, indicate that sailaba cultivation has decreased from 0.33 million ha in 1980 to 0.17 million ha in 2000 [8]. The floodwater in the sailaba system is collected in two different ways: troughing the *bandat* systems and diversion of ephemeral streams.

Bandat systems are large bunds (embankments) made by farmers in the bottom of the valleys to serve as filed demarcation boundaries and to trap runoff water. In this system, 0.6–3 m high bunds (earth embankments), depending on the topography of the land, are constructed on the main seasonal riverbeds to divert floodwater and lead it to the bounded fields [16]. The floodwater originating from the upper Loralai district flows through parts of Loralai, Kohlu, and Sibi before entering the Sind province. The bounds have been traditionally built by animal labor (camels and bullocks) but now it is common to see the increasing use of bulldozers and tractors. The bund areas are simply banks of earth. Farmers raise their crops on areas where the runoff is collected.

FIGURE 25.12 Sailaba at Wali Tangi (Valley) Quetta, Balochistan.

FIGURE 25.13 Khushkhaba Balochistan, Pakistan.

Diversion of ephemeral streams is another common practice in upland Balochistan used for agriculture and domestic water supply. The diversion of ephemeral streams is to trace stony land alongside ephemeral streams at the top of the valley, near the mountains and to divert the stream flow into the fields by dams extending into the streambeds (Figure 25.13). Stream flow generally occurs following the intense storms of the monsoon period, bringing sediments from the surrounding hills, which provide nutrients for crop production [24].

25.3.5.1.3 Khushkhaba System

The khushkhaba system comprises in situ conservation of incidental rainwater and catching runoff from large uncultivated blocks and diverting it to cultivated fields. Fields receive water directly from precipitation or from localized runoff. The khushkhaba is merely a chance cropping with a successful crop being raised on average once in 5 years. The main difference between the khushkaba lands and the sailaba (flood) lands is that the catchments area of the former is small and is often not bigger than the field enclosed by the embankment or bund. Embankments are made facing the hills, so that the natural gradient within the bunded area helps collect the runoff above the embankments [13]. The area inside the bund is deliberately left uneven with the areas floes to the bund being the lowest (Figure 25.13). This is done so that, in the case of high rainfall, the runoff from adjacent areas upslope collects near the embankments and provides enough water at least to grow corps in the lower half of the fields (0.5%–1% slope), and to encourage rainfall to runoff into the tilled bunded field below to increase both its soil moisture content and, consequently, the yield of the dryland crop. It is mainly practiced in the Quetta-Sarwan and Zhob-Loralai areas of the Balochistan province. The area under khushkhaba cultivation in Balochistan was estimated as 0.32 million ha in 1990 and 0.34 million ha in 2000 [8].

25.3.5.1.4 Tarai System

The most common type of water conservation in the arid region of Sind, Pakistan, is a dugout commonly caled *tarai.* Tarais collect rainwater for water supply and are filled from the water drained from a leveled watershed and collecting area (Figure 25.14). They could be dug cheaply in low-laying areas with clay soil where there is some runoff. The depth of water in a tarai is normally 3–4 m. The water from tarais, which is less than 3 m deep, is fast lost through evaporation. The evaporation rate is relative to the amount of

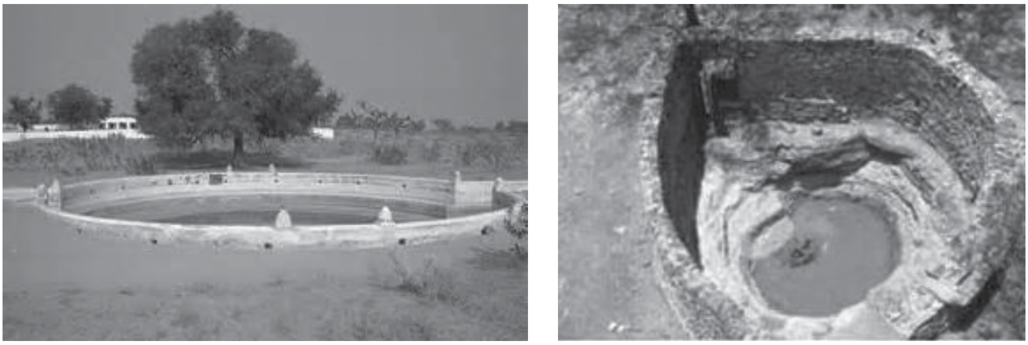


FIGURE 25.14 Tarai system at Thar Desert, Southeastern Sind, Pakistan.

runoff received and its frequency during a year. The evapotranspiration rate in drought-affected areas is significant, as there are prolonged dry spells with no rainfall or runoff received during the dry year. Therefore, the tarai depth is normally twice the annual evaporation in the area. They are dug so deep as to hold water for long periods. A tarai has sloping sides so that livestock can have access to water. Desalting is needed after 3–4 years.

25.3.5.1.5 Small Dams

Small dams on channels and streams, however, collect and store more water than tarais. Several such dams have been constructed in hilly and mountainous areas at some places on the stream to store rainwater. They are typical in the Kohistan area of the Sind and Balochistan provinces. The reservoirs of water in small dams can serve both animals and human beings. In the Kohistan region, particularly where many rainwater streams flow heavily during and after rainfall for a considerable period, such reservoirs retain water for some time after the end of the rainy season. The soil retains moisture for a longer period to support dryland agriculture (Figure 25.15). The system is also more suitable for the decrease in aridity and stability of the water table in the drought-affected areas not only in Pakistan but in the world as a whole.

FIGURE 25.15 Hina dam, Quetta, Balochistan.

(a) (b)

FIGURE 25.16 Well at (a) Turbat and (b) Washuk Districts, Balochistan.

25.3.5.1.6 Wells

In most of the rangelands, the dependable and common source of water is wells, where groundwater is of usable quality. Water from the well is raised manually or by animal power. The wells are usually dug along the riverbeds and channels to harvest the shallow seepage water (Figure 25.16).

25.3.5.1.7 Effectiveness of Traditional Water Conservation during Drought

The efficiency of the traditional karez systems had been negatively affected during the last 20 years for two reasons: first, due to recurring droughts, and second due to the installation of a large number of tube wells and dug wells (above 25,000 functional tube wells exist throughout Balochistan at present). The rate of depletion of groundwater in Balochistan has been accelerated from approximately 0.2 m per year prior to 1989 to the present rate of 1–1.5 m per year [15]. The installation of a large number of tube wells has contributed significantly to lowering the groundwater table, which has dropped from 15 to 80 m in the last 30 years. The latest drought has devastated the entire ecosystem as water supplies for domestic use, agriculture, and vegetation recede or vanish altogether. A key advantage of the karez is that it delivers water all year round, even in the year when rainfall is below average. According to Appell et al. [5], during the recent drought in Balochistan, the karez continued to deliver enough water to meet the people's needs for about 2 years. However, due to the continuous drought condition, natural flows in karezes and springs are also drying up. Community-owned and maintained karezes were replaced by private wells owned by a few individuals.

During the last decade, the government departments, National Rural Support Programme, and non-government organizations working in the area have restored nearly 200 karezes. Till July 2002, the National Rural Support Programme and its community organizations had rehabilitated 112 karezes in Turbat, benefiting over 13,000 households [5]. In some areas, including those close to the Dasht River, the karez is a vital link to water storage facilities. The government has recently built a number of water storage bunds, which are also linked to the karez system and play a vital rule in the well-being of the communities in the drought-affected areas of Balochistan.

Sailaba and khushkhaba systems are more affective for the conservation of the rain or floodwater in the arid Balochistan and Sind provinces. Crops growing under these irrigation systems give poor yield and return and thus the investments are very risky. However, the farming systems in conjunction with livestock do provide an off-farming income, which is the major source for many of the poor farming communities. These types of water harvesting systems are dependent on the monsoon, which is unreliable in upland Balochistan. Due to below-normal rainfall during the past 60 years, many parts could not receive enough rains to recharge the water table. The abrupt decline in rainfall in most of the uplands has caused complete drying of water sources for domestic needs throughout the arid region in Pakistan.

The long period of moisture stress during the drought coupled with shallow rooting results in very low yields. Both sailaba and khushkhaba are managed in traditional ways. These systems serve only to meet the barest needs of the farmers. In the most severe drought-affected areas of Balochistan and Sind provinces, cropping of khushkhaba and sailaba types has totally disappeared. In areas severely or moderately affected by drought, crop area has reduced by 60%–80% with the productivity going down by almost 50% due to moisture stress. Streamflows available for sailaba cultivation have either totally dried up or drastically reduced because of the failure of rainfall [6]. The areas under wheat, barley, and sorghum have registered a drastic reduction of 84%, and 96%, respectively.

During the drought and dry spells of the last 20 years (1990–2010), the floodwater was received in reduced quantity and, consequently, the command area was severely affected. The farmers either harvested the wilted crop or could not cultivate due to water scarcity.

Tarais, small dams, and wells are common sources of water conservation in the drought-affected areas of the Sind province, Pakistan. In Sind, very limited efforts have been made to accumulate the rainwater that may be utilized for cultivation of land. Several projects like the Mole dam, Kacho reservoir, and development of lakes, depressions, and reservoirs are lying unattended and ignored for many years, which has caused a serious problem of water scarcity for the inhabitants of the southeastern Sind in 2013–2014. These water bodies can substantially harvest the rainwater for using it for valued crops and water supply for domestic use during dry years. During the drought of 2000, the districts of Tharparkar, Khotan, and Dadu were severely affected and tarais either dried up completely or became heavily polluted. The other water sources like ponds have dried up due to extreme drought, and water level in the wells have also fallen. With the drying up of sources of water, the herders had to move 10–12 km to water their animals and, during extreme scarcity, they migrated to irrigated areas [10]. Due to lack of moisture, crops such as millet, guar, and grasses have dried up completely and overgrazing has caused poor vegetative cover, resulting in desertification.

25.3.6 Modern Water Harvesting and Conservation Methods

25.3.6.1 Runoff–Run-On Systems for Khushkhaba Areas

The dryland farming system of upland Balochistan faces many constraints mainly due to low and erratic rainfall, which varies from 150 to 300 mm annually. The dryland farmers classify 3–5 years out of 10 as a poor crop year with low grains and fodder yields. The farmers have therefore developed several water-harvesting practices that minimize production risks. Based on the observations of the valley bottom soils, Rees et al. [24] suggested more modest and practical interventions. Since crop growth in the upper portions of most fields is usually patchy and poor, the possibility of treating this unproductive land lies in reducing infiltration of rainwater and increased run-on in the cropping area near the bund. The upper portion was treated either by plowing to remove vegetation and loosening the soil or by heavy planking to pulverize and level the soil or by wetting to induce crust formation. This wetting can be artificial, using an outside source of water or the first rain of the season will cause crust formation after the pulverization treatment of the soil. Other treatments such as concreting or mixing salt with soil to engender a strongly impermeable crust are possible but these are much more expensive than the treatment explained earlier. These interventions have resulted in additional soil moisture storage in the cropping area near the bunds.

25.3.6.2 Water Ponds and Storage Tanks

The available water resources in mountains and deserts of Balochistan have often a small discharge, and the direct application of this low flow results in higher conveyance and application losses. A standard-size water pond is an integral component of a farm's infrastructure throughout Balochistan (Figure 25.17). Before the rains, people normally constructed small ponds, which are either mud plastered or cemented, to store/conserve rainwater for domestic use and, in some cases, for animals. The size of these ponds varies from place to place. The stored water is available for a period 4–6 months, depending on the size of the ponds, prevailing weather conditions, and its use [2]. Water ponds constructed in these areas conserve

FIGURE 25.17 Water tank at Thar and Cholistan Deserts, Sind.

water by increasing the volumetric flow through its intermittent and timely releases. The advantage of these ponds is that farmers keep their ponds filled round the clock, using them as and when the need arises, and selling this water to neighbors. An additional advantage is that earthen ponds also recharge the groundwater in the desert or drought-affected area and play a vital role in the emergency water supply for domestic use during drought periods.

25.3.6.3 Artificial Recharge to Groundwater

Due to the continuous overdraft, Balochistan groundwater aquifers are dropping at 3.5 m annually. In Sind, less rainfall and reduced flow of water in rivers and canals have also affected the groundwater recharge, resulting in the progressive lowering of the water table. Reduced stream flow has particularly affected the dug wells along their course, creating a serious drinking water problem. The most critical issue, therefore, in both provinces is how to stabilize and maintain the groundwater table. One possible solution is artificial recharge of groundwater. The artificial recharge techniques include plantation of appropriate plant species, inverted wells, recharge dams, loose-tone check dams, deep-dug wells, ponds and recharge basins, depression, benching, spreading of water, and divert or link canals from nearby perennial rivers.

25.3.6.3.1 Plantation

Plantation reduces the rate of runoff by trapping and delaying the water-associated reductions in the level of silt carried in the floodwater. This technique results in a significant impact on water conservation and improvement in Balochistan, having sufficient soil cover. Studies reported that an 80 mm storm of rainfall on vegetative catchments could produce a lower peak flow than that from a 20 mm storm in catchments without plantation. It is also reported that the vegetative measures can add around 33% more to the groundwater recharge [20].

25.3.6.3.2 Recharge Dams (Delay-Action Dams)

This technique consists of constructing dams across streams to store floodwater for recharging of groundwater. The dams delay the passage of floodwater by retaining it behind impoundment structures. The recharge then takes place by infiltration behind the structures through the reservoir bed. A number of such dams have been built in Balochistan and Sind over the last two decades. These are popularly known as delay-action dams.

Unfortunately, many of these do not have any means of releasing water downstream of the dam. Typically, they have high initial recharge rates due to high porosity of the bed, but these rates then fall exponentially with each rainstorm due to the high silt load brought in by the floodwater. A limited case study on the effectiveness of such dams was conducted on the Pechi delay-action dam near Ziarat using the water balance isotopic and chemical techniques. The purpose of the dam was to collect rainwater in the flood season and to supplement the nearby karezes by recharging groundwater. The study failed to establish any hydraulic interconnection between the dam reservoir and downstream karezes. The main reason was sedimentation of finer materials in the reservoir bed [23].

25.3.6.3.3 Recharge Wells

The technique basically consists of drilling a borehole to provide a direct path for water to infiltrate and to recharge the groundwater. The water may flow under gravity or may be injected through reverse pumping. A dug well can also be used as a recharging device.

Unfortunately, very often a precipitation of less than 25 mm occurs, which seldom results in any runoff. Rainfall of more than 25 mm often occurs after a long dry spell and is not effective. Occasional precipitation causing a runoff carries a large amount of sediment, which is harmful to the success of artificial recharge practices in Balochistan.

25.3.6.3.4 Hand Pump

In areas where the groundwater tables are not very deep, the hand pump is the best solution for domestic water supplies. One hand pump is sufficient for some 50 persons. Furthermore, the local communities welcomed this technological intervention as it is easier, time saving, water saving, and cheaper (Figure 25.18). But, it is more suitable if the hand pump is installed at a public place or at a community center, so that everyone has access to water. The tube wells are also very affective for the drought-affected areas but it is dangerous to the water table depletion.

25.3.6.3.5 Improved Tillage and Furrow-Ridge Planting

Although this is not strictly a drought-proofing measure, improved tillage may lead to increased yields, which is important for creating food reserves. The effect of tillage on crop growth and yield is not only to increase infiltration of rainwater but also to break the hardpan, which allows better root growth or increased nitrogen mineralization of the inverted soil.

Farmers in Balochistan are using a dual purpose plowing and planting implement, the "desi-plow." This produces ridges 8–15 cm high, depending on the soil type and pushes the loose soil to either side to form a ridge-furrow system. This enables farmers to place seeds in moist soil by planting 4–6 cm below the bottom of the furrow.

(a) (b)

FIGURE 25.18 (a) Water hand pump Quetta and (b) Thar Desert, Sind.

FIGURE 25.19 Watercourse lining in mountain valleys, Balochistan.

25.3.6.3.6 High Efficiency Irrigation Technology

In most of Balochistan, irrigation methods commonly followed by farmers include the controlled flood irrigation technique on either wide border strips or basins. In some areas, where soil is sandy, gravity irrigation results in significant wastage of water due to seepage. Almost all fruits, vegetables, and winter fodder crops are overirrigated. This technique not only helps in agriculture activities in the drought-affected areas but it also helps for the recharging of water table and water supplies for domestic use.

25.3.6.3.7 Watercourse Improvement

Considerable wastage of water occurs in watercourses. The main causes of operational losses are seepage, overflow, vegetation, and rodent holes. It is therefore required to fill the water courses with rocks, flat stones, sand, etc. However, cemented watercourses are not recommended as it will stop the seepage of water and cause depletion of the water table (Figure 25.19).

25.3.6.3.8 Furrow-Bed Irrigation

The basin irrigation method is commonly used in the drought-affected areas of the Sind and Balochistan provinces, with the highest water consumption and the lowest use efficiency. Furrow-bed irrigation is considered the most efficient method of water application. Raising row crops like cotton on beds with row-to-row spacing of 75 cm is gaining popularity amongst the framers, mainly because it saves water; the cost of the crops' production is also substantially reduced.

25.4 Summary and Conclusions

Drought management planning has effective strategies for water resource to reduce risks and impacts associated with droughts. Most commonly, there are many components in a drought plan, but the most outstanding and reliable solutions for drought-affected areas are as follows:

- To improve water utilization efficiency.
- To increase the use of groundwater through improved and new wells.
- To establish irrigation control systems.
- To increase the use of wind power to increase groundwater utilization.

- The population growth in the arid and semiarid areas of Pakistan is very high, which not only affects the economy of the country but also causes changes in the availability of water resources and land utilization. Therefore, essential steps are needed for the control of population growth in the arid region of Pakistan.
- The rate of urban as well as rural sprawl is very high and inappropriate. Resultantly, most of the agriculture and forest lands are converted into residential areas. These anthropogenic activities affect the rate of evapotranspiration, exposed surface, potable water availability, etc. It is therefore essential to make a policy for the land use pattern for the arid region in Pakistan and to implement that properly without any refreshment stand.
- The literacy ratio in the arid region of Pakistan is less than two persons in 1998, and it is very hard to implement drought-adaptive programs without any improvement in the literacy ratio. It is therefore necessary to establish education institutes throughout the length and breadth of the arid region and to educate the people regarding drought and water resources policies, its importance, and its role in community development.
- To prevent overgrazing, the number of animals to be fed in a certain area must be kept within the carrying capacity of the grasslands.
- Legislation is needed to prevent wanton cutting of forests and also to ensure the immediate replanting of trees cleared for lumbering and domestic use.
- Both monoculture and overintensive multicropping are unsatisfactory because they exhaust the soil. Crop rotation, however, allows a wide range of crops to be grown without allowing the field to lie fallow but without depleting the soil. By growing different crops in successive years in the same field, plant nutrients used by one crop can be replaced by another. Therefore, crop rotation as well as mixed farming in the drought-affected area of the country is very appreciable for the soil fertility.
- For the flow and exploitation of water, well-developed canal systems, and the use of seasonal dams, tank irrigation is more appreciable as compared to other sources of irrigation. For this purpose, it is necessary to establish seasonal dams and barrages over the Indus River, particularly in Sind and lower Punjab. It will not only raise the level of the water table but also ensure the availability of water for the inhabitants of these areas.
- Waterlogging and salinization not only increases the salinity of soil and water but it also increases the reflection of the outgoing radiation, particularly in Punjab and Sind. To save soil from salinization, the reduction of riverbank filtration is very important. Therefore, proper planning is needed for the control of waterlogging and salinization in the lower latitude of Pakistan.
- With regard to water quality and human requirements, perhaps the best results can be obtained by using artificial recharge of saline as well as ocean water, a process whereby pretreated river water is made to enter an aquifer in one way or another. The recharge of water may also be contributing to a deeper water table. Furthermore, there is a need to arrange for adequate protection of the water-catchment areas on the mountain-tops, which are indispensable for the recharge of the groundwater table in the arid lowlands of the country. So, a proper planning is needed for this achievable recharging of water in the coastal as well as the entire areas of Sind and Punjab.
- To overcome the water scarcity in the arid Balochistan province, it is necessary to construct a bypass/divert canal from the Indus River at the Kohat district and to drop the extra flow of the Indus River during flood season into the Zhob River. The river covers a major part of the Balochistan province and will help in the irrigation system as well as recharging of the water table in the area. This effort of the government of Pakistan will also call for a step toward green Balochistan.
- The existing system of monitoring drought and its impacts on various sectors is weak. The dissemination and sharing of the available information, due to the civil society between and across government departments with organizations outside government system, are limited. There is a need to develop a policy for the access to information related to drought and water management. Such information databases are limited at present. A similar situation exists at the regional level. Sharing and exchange

of information regarding drought monitoring and impact assessment are also limited among the countries of the region.

- Both target areas considered in this document have limited water resources in areas outside the Indus basin. Still, they do not make efficient use of the available resources. Farmers are not aware of actual crop water requirement, and irrigation-scheduling practices are still largely based on the amount of water available to the farmer and the situation of the farm. Farmers tend to overirrigate to cover the unleveled fields.
- Efforts are needed to help farmers in efficient conveyance and application of pumped groundwater. The water management technologies developed in the Indus basin regarding conveyance and application of water at the farm are very promising, as Pakistan is ahead of the countries in the region. Even then, such technologies were hardly tested and adapted in the drought-affected areas. Pakistan can provide a unique opportunity to share the experiences of the watercourse improvement program, laser leveling, furrow-bed irrigation, skimming wells, and salinity management.
- Similarly, Pakistan can learn from India and Iran in the areas of the drip and sprinkler irrigation systems, as both of these countries are ahead in this regard. A regional research and development program for drought and water management seems justified for exchanging experiences and knowledge and building future activities.
- Farmers should be encouraged and motivated to use indigenous water harvesting technologies for sailaba and khushkhaba areas. There is a need to understand the traditional systems of sailaba and khushkhaba and suggest improvements within the existing framework, instead of introducing conventional surface irrigation schemes. The use of local knowledge and wisdom is essential along with active participation of local water user institutions. Pakistan is ahead in the field of developing the sailaba irrigation as such a system has been in place since 3000 BC (Indus civilization). These systems of after spreading, if integrated with recharging the groundwater, can provide a cost-effective intervention for mitigating drought impacts. The spate irrigation development provides a workable option for the normal years and such systems do not provide water during droughts. The population has to migrate from these areas during the drought. Therefore, provision of water storage dams can provide a source of small-scale irrigation for the drought periods as a source for supplemental irrigation. Provision of water for high value agriculture in sailaba systems would be the ultimate goal of mitigating the impacts of drought.
- Due to the excessive exploitation of groundwater, coupled with successive droughts, the water tables in different parts of Sind, especially in Balochistan, have declined considerably. In Balochistan, even the karez groundwater irrigation system has dried up. This overexploitation of resources has caused devastating impacts on drinking water supplied for the urban and rural population. For conservation of the resource, the government needs to develop appropriate policies to effectively manage and monitor groundwater development and use. Steps should be taken for the revision and enforcement of water laws. Communities should be directly involved in the campaign of recharging the aquifers and in the conjunctive use, and the management of surface water has to be used and adapted in the drought-affected areas of Balochistan and Sind provinces. Such experiences, if translated for the nonirrigated area, can provide excellent examples for the countries of the region.
- The use of efficient irrigation methods, farm layout, balanced use of fertilizers and pesticides, and integrated nutrient management remain limited and is one of the key factors underlying low productivity in Sind and Balochistan. A program of breeding and election of crops varieties, which can extract water from a deeper level, should be established. Such varieties, coupled with water management, can revolutionize sailaba areas.
- Farmers should be encouraged, motivated, and trained in the adaptation of efficient water use technologies such as sprinkler and drip irrigation, laser leveling, raised-bed planting, rainwater harvesting, watercourse lining, and water storage tanks, which have proven successful in different arid environments of Pakistan. The involvement of the private sector in the provision of services to farmers is the only workable option, as the public sector institutions are not tuned to provide service in this regard.

- A drought mitigation plan is essential for the drought-affected areas particularly Thal, Nara, Thar, Kharan, and Cholistan deserts in Balochistan and Sind. This should also include climate change impacts on the availability of water resources and developing coping mechanisms to address the drought impacts. In fact, such a plan has to be integrated in the overall perspective development plan so that all the sectoral development plans should look into drought mitigation aspects in their routine development activities.
- Presently, there is no comprehensive drought mitigation infrastructure and strategy at the federal and provincial levels. Contrary to the well-established food mitigation with adequate institutional arrangements, the drought mitigation activities are, by and large, managed on an ad hoc basis. Institutional arrangements and their capacities are inadequate at the federal and provincial levels to effectively launch the early warning systems, preparedness and contingency plans, and rehabilitation measures, while such arrangements are nonexistent at the district level. In fact, this is the weak area in the region as a whole. This justifies a regional initiative to evaluate the existing institutional setup and mechanisms for drought mitigation and build an effective structure and mechanism, which can be adopted by the countries of the region.

  To mitigate the drought impacts, it is essential to formulate and adopt a national drought policy on a priority basis. The suggested guiding principles for the formulation of the national drought policy include the following:
  - Favor preparedness over insurance, insurance over relief, and incentives over regulations.
  - Set research priorities to address the needs of rural communities and urban households considering the effectiveness and limitations of the existing coping mechanisms.
  - Coordinate the activities of the drought mitigation service at the federal, provincial, and district levels.
  - Participation of the public representative and the civil society is an essential element of any policy.
  - A consultation and communication strategy should be formulated while developing the national drought policy. The purpose is to build understanding and ownership of the policy by all the stakeholders.
  - Sharing and exchange of experience from the countries of the regions having similarities.
- Preparedness, which includes drought planning, plan implementation, proactive mitigation, risk management, resources stewardship, consideration of environmental concerns, and public perception and drought literacy should be the elements of the new policy. This policy would require a shift from the current emphasis on ad hoc relief measures to the proactive risk management.
- For implementation of the national drought and water resource policy, there is a need to establish an apex organization for the planning, coordination, and monitoring of the policy interventions at the federal level. This organization may be entrusted with the responsibility of providing an enabling framework to the provincial government, where they are motivated to establish a similar organizational setup at the provincial levels to provide linkages and coordination among the line department and the district governments. A consultation input will be required to prepare the outline for the proposed at the federal and provincial levels. At the district level, a district drought mitigation committee would be required to implement and monitor the programs as envisaged by the federal and provincial governments.

There is a need to develop a regional research and development program for drought mitigation and water management through active involvement of national as well as international organizations. It should aim at sharing and exchange of existing knowledge and information between participating countries, studying the policy and institutional aspects under each participating country's national program, encouraging testing and adoption of successful interventions in the participating countries, and evaluating the impacts of socioeconomic and political changes on the policies of drought and water management in the region.

Authors

Saifullah Khan was born in the evergreen Swat valley ("heaven of the universe" and historical place), Khyber Pakhtunkhwa, Pakistan, on April 28, 1970, in the home of (Late) Haji Muhammad, who was the first school teacher and founder of the education system in the Swat valley during the English era. Professor Saifullah Khan did his MPhil in climatology from the Institute of Geography, University of Peshawar, in 1997–2003 under the supervision of Prof. Dr. Mahmood-Ul-Hasan (geomorphologist). During his MPhil, he developed his first research-based methodology for the climate classification of Pakistan, which is also applicable to any part of the world and provides a base for future researchers to reach out to the problems of climate change and related disciplines. During his PhD from the same institute, he studied climate change adaptation and its mitigation to agriculture sectors in the arid regions of Pakistan over a period of 14 years (2003–2014). A number of predictions about the climate change scenario were made, and for the first time, he presented the importance of people's perception in the climate change phenomena on an international level. Professor Khan is a confident and enthusiastic person with the ability to learn and adapt quickly to new challenges and to handle difficult situations under pressure. He has 18 years of technical/research experience in GIS and remote sensing, particularly in land record information system, telecommunication, land use, education, forests, demography, political divisions, urban ecology, hydrology, oceanography, archeology, anthropology, history, and philosophy.

During his career, he has published more than 60 research papers and five books on different disciplines at the national as well as international levels. The conferences he has affiliation to and attended are USEPAM (Vietnam), BALWOIS (Macedonia), Pre 11 (Greece), CEST (Greece), GEO MED (Turkey), ICCSA (Vietnam), Geo Alb (Kosovo), and BAS (Bulgaria).

Professor Khan began his professional life as a GIS field surveyor and moved to being technician, GIS developer, GIS specialist, coordinator, deputy manager, manager, senior project manager, consultant, freelancer, and is currently a professor. During his 21-year career, he has served the British Council, HQ NADRA, Ministry of Information Technology, Ministry of Environment, Population Census Organization and Statistical Division, DFID, GTZ, FINCON International, Geographic Information Center, Institute of Geography University of Peshawar, and currently in the Institute of Social Sciences, Directorate of Distance Education, Bahaudin Zakariya University, Multan, Southern Punjab, Pakistan. Professor Khan has an organized approach with good communication skills, which enables him to work effectively either on his own or as part of a team in the fields of GIS/RS, climate change, environment, disaster management, forestry, hydrology, and archeology.

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26

Forest Fire Mitigation under Water Shortage

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Abstract Fires are a natural part of many forest ecosystems. Nonetheless, the massive blaze that raged in Alberta, Canada, in May 2016 was catastrophic, threatening human health, the economy, and the environment. The fire displaced more than 80,000 people and captured the attention of the world's media. Globally, fire mitigation and control under water shortage conditions have gained significant attention due to the effects of climate change and land management practices, which have produced more extreme environmental conditions. This chapter explores the factors and associated aspects of this subject. As expected, drought identification and assessment are significant elements to be considered, hand in hand with water shortage, as facilitating the outbreak of forest fires. The interrelationship between drought and fire is examined, along with the impact of drought on fires and water shortage. In addition, a description of forest fires is considered, including the definitions and categories of forest fires, forest fire meteorology, as well as an explanation of the causes and factors affecting forest fires. Moreover, forest fire mitigation is presented. This is followed by forest fire monitoring, which includes aspects of early warning systems, remote sensing techniques, and risk assessment. Finally, forest fire assessment is deliberated, including the methods applied for the delineation of burned areas.

26.1 Introduction

Water shortage leading to scarcity affects numerous parts of the world, especially semiarid and arid regions, such as the Mediterranean. Undeniably, the said scarcity often comprises the adverse result of the lack of sufficient water in these regions, compounded by ineffective policies of water resources management. If one adds the presence of prolonged drought periods to the equation, potentially aggravated by increased climate variability and climate change, and subsequently includes contemporary water overuse and misuse combined with ever-increasing water demands, the result is water scarcity [63].

Drought is a natural phenomenon recurring at a regional scale throughout history. Indeed, drought is considered as one of the major natural hazards with a significant impact to the environment, society, agriculture, and economy. Drought is also considered as an insidious natural hazard characterized by lower than expected or below normal precipitation that, when extended over a season or longer periods of time, is insufficient to meet the demands of human activities and the environment [62]. As previously mentioned, extended drought periods are one of the factors and components leading to water scarcity. There is a wide variety of sectors affected by drought due to its diverse spatial and temporal distribution [24]. Moreover, there are several special drought features, such as its nonstructural effects, or its slow onset, or even the lack of a universal consideration of drought as a hazard [61]. Furthermore, there are severe impacts of droughts, which are indirect and not definitely measured, resulting in diverse difficulties in drought assessment and response, which can cause delay or lack of progress on drought preparedness plans and mitigation measures.

Wildfires, on the other hand, are "quasinatural" hazards, that is, they are not entirely natural features, such as volcanoes and earthquakes, due to the common anthropogenic component in their initiation. Principal natural sources of wildfires are lightning, volcanic eruption, sparks from rock falls, and spontaneous combustion. Nonetheless, the main source of wildfires is anthropogenic activities, with only a portion attributed to environmental origin. These actions include arson, campfires, controlled agricultural burning, discarded cigarettes, sparks from equipment, and power line arcs. In certain societies, the practice of slash and burn farming is still employed as a method of clearing land rapidly for subsequent cultivation. These areas of land are exploited until the soil loses fertility from the time it is abandoned to fallow, creating an idyllic habitat for grasses, which, when subjected to low soil humidity, are prone to combustion. Vegetation fires are a global phenomenon occurring in tropical, temperate, and boreal regions. Biomass burning is a regular feature in the tropical forests of Brazil and Indonesia; temperate forests of the United States and Europe; boreal forests of Siberia, China, and Canada; tropical savannas of Africa; and agricultural lands of the United States and Europe.

This chapter deals with the mitigation and monitoring of forest fires that are driven and caused by natural factors, such as water shortage or water scarcity. As anticipated, drought identification and assessment is a significant component to be considered, along with water shortage, as conduits to forest fires. The chapter is organized as follows: in Section 26.2, the relation and interaction between drought and fire is examined, along with the impact of drought on fires and the water shortage aspect. This is followed by a presentation of forest fires in Section 26.3, which includes definitions and types of forest fires, forest fire meteorology, as well as a description of the causes and factors affecting forest fires. In Section 26.4, the forest fires mitigation is presented. Section 26.5 focuses on the monitoring of forest fires, including early warning systems, remote sensing techniques, and risk assessment. Finally, Section 26.6 centers on forest fire assessment and details methods for the delineation of burned areas.

26.2 Drought and Fire

With the basic characteristics of drought involving a lack or deficit of precipitation, it is critical to have reliable and long-term records of precipitation for the effective identification of an impending drought situation. Traditional methods of drought assessment and monitoring rely on rainfall data, which are often limited in a region, and may be subject to inaccuracies in measurement and data archiving.

Furthermore, in many instances, these data are not available in near real time, with records often submitted to regional centers 1 or 2 months after the data were locally registered. If the precipitation distribution for a region is typically seasonal, then a shortage of precipitation over this time frame is not necessarily an indication of the initiation of a drought. Thus, it is imperative to determine the "crucial" period(s) of precipitation for any region with respect to drought. Although precipitation is the basis of many drought indicators, other variables such as temperature, soil moisture, unregulated base stream flows, potential evapotranspiration, and, for longer duration events, groundwater levels, can be significant in the assessment and monitoring of drought severity.

It is recognized that there is no universally accepted definition of drought. There is, however, a tendency to characterize diverse types of drought, such as meteorological, agricultural, hydrological, and socioeconomic drought. Indeed, a meteorological drought is characterized by a significant period of time with substantially less than average precipitation amounts, which corresponds to the general definition of drought. A meteorological drought is usually defined as the degree of dryness specified by precipitation deficiencies, as compared to some "normal" or average amount, and by the duration of the dry period [60]. For the identification of the meteorological drought, a threshold of precipitation deficiency over some predetermined time period is customarily considered. Nevertheless, the onset of other types of drought, such as agricultural or hydrological drought, starts with the inception of the meteorological drought, which then continues to prevail long enough to impact the agricultural and/or the hydrological sectors [9,10].

Wildfires occur when all the necessary elements of a fire triangle come together in a predisposed area. Specifically, an ignition source is brought into contact with a combustible material, such as vegetation that is subjected to sufficient heat and has an adequate supply of oxygen from the ambient air. Indeed, high moisture content usually prevents ignition and slows propagation, as higher temperatures are required to evaporate any water within the material and heat it to its ignition point. Dense forests typically provide more shade, resulting in lower ambient temperatures and greater humidity and are, consequently, less susceptible to wildfires. To some degree, forest management practices can be partially imputed for wildfires, as often areas of deadwood are left to accumulate and, subsequently, the potential for large and destructive fires proliferates. As public agencies assigned to the management of forests improve management practices to those that recognize the role of fire in maintaining forest health, the impacts of climate variability on fire management become more prominent. Years of excess precipitation followed by warm periods can encourage more extensive fires and result in longer fire seasons due to accumulated vegetation. Heat waves, droughts, cyclical climate changes, for instance, El Niño, and regional weather patterns, such as high-pressure ridges, can increase the risk and radically amend the behavior of wildfires. Since the mid-1980s, earlier snowmelt and associated warming has also been linked with an increase in length and severity of the wildfire season in the western United States [59].

Diurnal dynamics: Fire intensity also upsurges during daytime hours, with burn rates of smouldering logs up to five times greater due to lower humidity, increased temperatures, and higher wind speed. Sunlight irradiates the ground during diurnal hours, which generates air currents that travel uphill. Conversely, at night, the land cools, creating air currents that travel in the opposite direction. Wildfires are fanned by these winds and often follow the air currents over the hills and through valleys [36]. This phenomenon is known as the slope effect.

26.2.1 Impact of Drought on Fire

Plants continuously lose water through evapotranspiration. Nevertheless, this water loss is usually balanced by water absorbed from the soil, as humidity, or precipitation. When equilibrium is not maintained, often due to droughts, plants desiccate and as a result become more flammable. Wildfires are common in climates that are sufficiently moist to allow for the growth of vegetation but feature extended dry and hot periods [45]. Fires can be particularly intensive during days of strong winds, periods of drought, as well as during warm summer months. It has been stated that global warming may increase the severity and frequency of droughts in many regions, creating more intense and frequent wildfires [40]. Climate variability, in the form of prolonged periods of drought, can potentially leave forests tinder dry and, accordingly, susceptible to more intense fires. On the other hand, it is important to clarify that wildfires do not occur during droughts unless they are accompanied by other factors, such as lightning and strong winds [65].

26.2.1.1 History of Drought Impact on Fire

Evidence of fire is first found in the Carboniferous age, 400 million years ago, in the form of fossilized charcoal in coal deposits. Low atmospheric oxygen during the Middle and Late Devonian was accompanied by a decrease in charcoal abundance [13,22]. Additional charcoal evidence suggests that fires continued through the Carboniferous period. Later, the overall increase of atmospheric oxygen from 13% in the Late Devonian to 30%–31% by the Late Permian was accompanied by a more widespread distribution of wildfires [51]. Later, a decrease in wildfire-related charcoal deposits from the late Permian to the Triassic periods is explained by a decrease in the oxygen levels. Wildfires during the Palaeozoic and Mesozoic periods followed patterns similar to fires that occur in recent periods. In Jurassic gymnosperm forests, there is an evidence of high-frequency and light-surface fires. The increase of fire activity in the late Tertiary is possibly due to the increase of C4-type grasses. As these grasses shifted to more mesic habitats, their high flammability increased fire frequency, promoting grasslands over woodlands. However, fire-prone habitats may have contributed to the prominence of trees such as those of the genera Eucalyptus, Pinus, and Sequoia, which have a thick bark to withstand fires and employ serotiny [42].

Plants in wildfire-prone ecosystems often survive through adaptations to their local fire regime. Such adaptations include physical protection against heat, increased growth after a fire event, and flammable materials that encourage fire and may eliminate competition. For example, plants of the genus Eucalyptus contain flammable oils that encourage fire and hard sclerophyll leaves to resist heat and drought, ensuring their dominance over less fire-tolerant species [50]. Dense bark, shedding lower branches, and high water content in external structures may also protect trees from rising temperatures. Fire-resistant seeds and reserve shoots that sprout after a fire incite the preservation of species in a process called serotiny. Exposure to smoke from burning plants promotes germination of other types of plants by inducing the production of orange butenolide [14]. Grasslands in Western Sabah, Malaysian pine forests, and Indonesian Casuarina forests are believed to have resulted from previous periods of fire. Chamise deadwood litter is low in water content and flammable, and the shrub quickly sprouts after a fire. Cape lilies lie dormant until flames brush away the covering, then blossom almost overnight [45]. Sequoia relies on periodic fires to reduce competition, release seeds from their cones, and clear the soil and canopy for new growth [56]. Caribbean pine in Bahamian pine yards have adapted to and rely on low-intensity surface fires for survival and growth. The optimum fire frequency for growth is every 3–10 years. Too frequent fires favor herbaceous plants and infrequent fires favor species typical of Bahamian dry forests [41].

26.2.1.2 Effects of Water Stress on Growth and Development of Plants

During a drought, transpiration by plants may decrease, as plants attempt to conserve water. The magnitude of this decrease depends on the plant's root and leaf characteristics. The decrease in transpiration by phreatophytes, such as salt cedar, cottonwoods, Bermuda grass, and alfalfa is typically slight, since they are deep rooted and obtain their water from near the phreatic surface rather than from the overlying soil zone [23].

26.2.1.3 The Effect of Fire on Soil Properties

The thermal heat from a wildfire can cause significant weathering of rocks and boulders. Heat can rapidly expand a boulder, as well as disseminate thermal shock, which may result in structural failure. The application of aerial fire retardants creates an atypical appearance on land and water surfaces and has the potential to change the soil chemistry [55]. Fire retardants can decrease the availability of plant nutrients in the soil by increasing the acidity of the soil. Fire retardants may also affect the water quality through leaching, eutrophication, or misapplication. Dilution factors, including water body size, and precipitation, lessen the concentration and potency of the fire retardant. There is a continued concern about the effects of the fire retardant on land, water, wildlife habitats, and watershed quality. Yet, on the positive side, the fire retardant, specifically its nitrogen and phosphorus components, has been shown to have a fertilizing effect on nutrient-deprived soils and, consequently, creates a temporary increase in vegetation.

26.3 Forest Fires

Forest fires, also called wildfires, constitute one of the most widespread environmental hazards. This hazard contributes significantly to climate change and soil degradation [12]. The destruction of vegetation by forest fires can affect the land surface and the hydrological cycle, by increasing the surface albedo, surface runoff, decrease of evapotranspiration [34], increase of erosion, and occurrence of floods and deserts. Furthermore, the burning of biomass can contribute, along with gases, to the greenhouse effect and originate destruction of the ozone layer.

Forest fires have been a natural feature of wild lands' ecosystems in the lands bordering the Mediterranean basin. In fact, fire has played an important role in shaping many plant communities that grow in a climatic region characterized by very hot and dry summer conditions, with high evapotranspiration rates [4]. However, during the last three decades, human activities have disturbed the delicate natural balance between fire activity and the regeneration processes. Among the main reasons that can explain these facts, the following can be emphasized: abandonment of farmlands and forestry exploitations, urban expansion in forest areas, and the constant increase of tourist activities in wooded zones [4]. Focusing our attention momentarily in the Mediterranean region, forest fires occur in bordering countries of this area during the dry season, and mainly affect pine forests, brush lands, and less frequently cultivated fields. In the case of Greece, averages of about 2,000 forest fires are recorded annually. These fires affect a surface area of roughly 50,000 ha. Although the vast majority are small-scale fires, a minor number of them are considered as large-scale fires, burning very extended areas. In the United States, fires that burn more than 400 ha are considered large-scale fires [44]. Conversely, in Greece, large-scale fires are those that burn more than 100 ha [27]. These fires represent just over 5% of the annual totality of fires, but the associated burned area reaches 72% of the said total [12].

26.3.1 Definitions and Types

There are three types of forest fires, namely, ground, surface, and crown fires.

Ground fires, which burn on the ground or below ground vegetation, are often best controlled by excavating trenches or "firelines" down into the mineral soil layer, which cannot burn. When the fire reaches the fireline, it is starved of fuel and extinguishes itself. Ground fires are fed by subterranean roots, duff, and other buried organic matter. This fuel type is especially susceptible to ignition due to spotting, which is shedding burning biomass such as bark, to create a situation of rapid fire spreading known as spotting. Ignited fuel is blown ahead of an advancing fire front by strong winds to create "spot" fires [49]. In Australian bushfires, spot fires are known to occur as far as 20 km from the fire front [57].

Ground fires typically burn by smouldering and can burn slowly for days to months, as exemplified by peat fires.

Surface fires burn along the surface and tend to move quickly. Their fighting requires more manpower and equipment. Portable water backpacks and pumps (where a water supply is available), and firebreaks are the preferred control methods. These can be very labor-intensive strategies except in instances where machinery is available to clear the bush for the firebreaks. Crawling or surface fires are fuelled by low-lying vegetation, such as leaf and timber litter, debris, grass, and low-lying shrubbery.

Ladder fires consume material between low-level vegetation and tree canopies, such as small trees, downed logs, and vines.

Crown fires are most dangerous and spread the fastest. They occur on the tops of the trees, where fire can jump from crown to crown, often over firebreaks. Crown fires in extremely windy conditions have been known to jump rivers and even lakes. Fighting crown fires usually calls for extreme measures, generally aerial bombing with water and fire-retardant chemicals. Crown, canopy, or aerial fires burn the suspended material at the canopy level, such as tall trees, vines, and mosses. The ignition of a crown fire, termed crowning, is dependent on the density of the suspended material, canopy height, canopy continuity, and sufficient surface and ladder fires in order to reach the tree crowns.

26.3.2 Forest Meteorology

Meteorological parameters, such as rainfall, high temperature, low relative humidity, and wind velocity have a significant effect in the initiation and spread of forest fires. Nevertheless, the most significant of all the factors that affect the ignition and the spread of forest fires is the fuel moisture content.

26.3.2.1 Rainfall

A long-duration precipitation is capable of depositing significant amounts of water and drench the flammable forest matter, thereby, increasing its resistance to the initiation and spread of fire. On the other hand, as would be expected, a short-duration precipitation has a very low effect in increasing the fuel moisture. Besides precipitation, duration, and quantity, season also plays an important role. In Greece, during the summer months, often characterized by drought conditions and high temperatures, the possibility of a fire outbreak is incredibly high. A typical distribution of rainfall during the year is depicted in Figure 26.1.

26.3.2.2 Wind

The effect of wind on forest fires depends on its speed and direction. In particular, the wind speed is a very significant parameter for the initiation and spread of forest fires. Once ignited, the rate of the wildfire spread is closely related to the surface wind strength [49]. At the initial stages, the wind is the parameter that provides the necessary oxygen supply and, at the maturity stage, affects the propagation velocity through flame tilting. The mechanism that is similar to the slope effect dominates [27]. A wind speed that exceeds 2.8 m/s has been shown to have a 45% slope equivalent [52]. As a result, as wind speed increases, the oxygen supply escalates, and flames are forced more rapidly to neighboring areas through spotting. The wind direction is also important, because it determines the moisture content of the wind and the spread direction of the fire. Dry winds are more dangerous with respect to fire outbreak and spread. Large-scale fires show a high propagation velocity (2.5 km/h) and usually evolve to canopy fires and cannot be

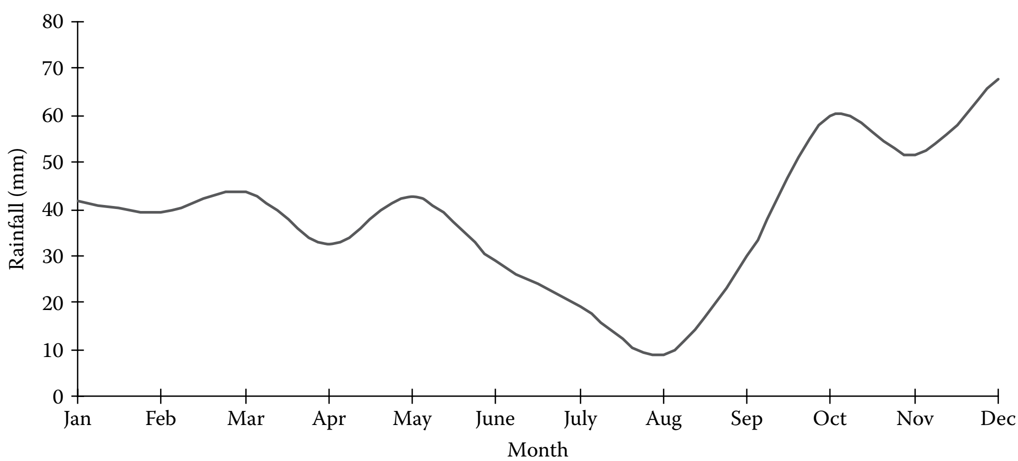

FIGURE 26.1 Indicative monthly rainfall for Larisa (mean of 13 years, 1985–1997), Greece.

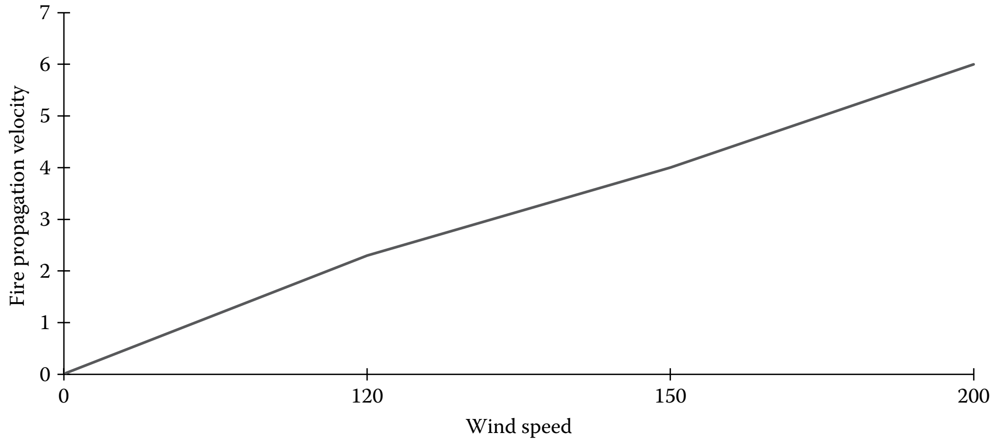

FIGURE 26.2 Propagation velocity of wildfire according to the wind speed.

theoretically described by quasi-steady-state models [48]. In Greece, such fires are closely related and affected by the prevailing strong winds (Figure 26.2). In a complex terrain where meteorological parameters are extremely variable, meteorological conditions derived from neighboring stations are usually not representative of fire conditions [52].

26.3.2.3 Temperature

High temperatures in combination with dry spells are extremely dangerous for the initiation and spread of wildfires. Most fire outbreaks occur near surface fronts, particularly in warm, dry conditions ahead of a well-developed cold front with an unstable temperature lapse rate and strong winds at low levels [49]. In Greece, the initiation of most of the forest fires occurs during noon hours, where the maximum temperatures and minimum relative humidity are recorded (Figure 26.3). Also, most forest fires in Greece occur during summer and early autumn, which are characterized by warm and dry conditions (Figure 26.4). Wildfires with a spatial extension over 500 ha habitually come about when the temperature is greater than 30°C.

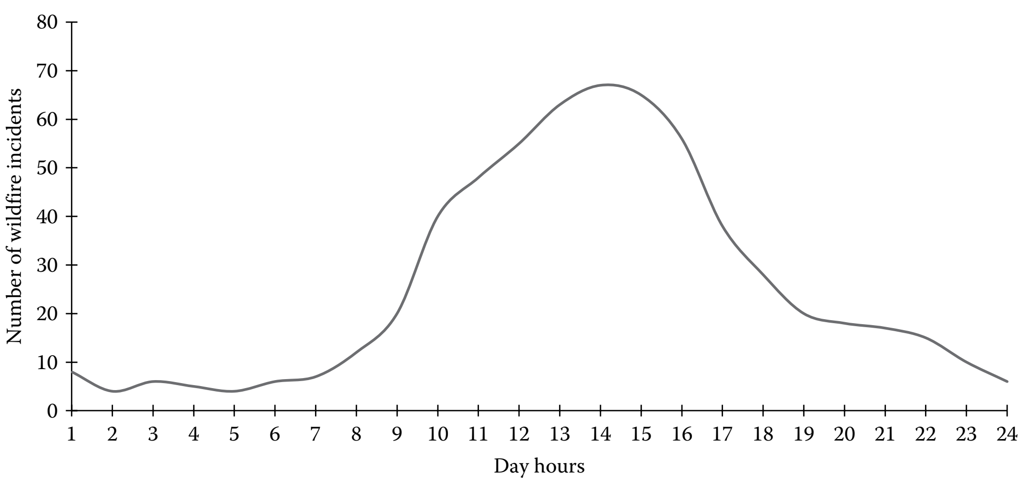

FIGURE 26.3 Initiation of forest fires during the day as a mean of 13 consecutive years (1985–1997).

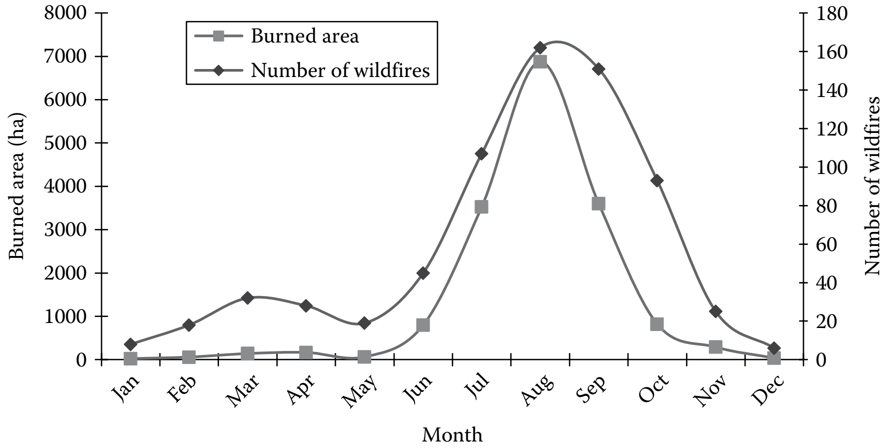

FIGURE 26.4 Number of forest fires and burned area during the year as a mean of 13 consecutive years (1985–1997).

26.3.2.4 Relative Humidity

Relative humidity is a significant factor according to the frequency and the propagation velocity of forest fires. It affects the number of incidents and their spatial extension (Table 26.1). Dry atmospheric air results in dry and highly flammable forest biomass, while during nighttime the increase of relative humidity results in the increase of the fuel moisture content. Among the other meteorological parameters, relative humidity determines the intensity of dehydration of dead organic material, and therefore the amount of ignition heat [52]. In Greece, it is stated that when the relative humidity is between 31% and 60%, 67.6% of fire occurrences are observed [27]. Several fires were, nonetheless, observed when the relative humidity was above 60%, which is unusual. This can be attributed to the fact that in Greece 86% of fires occurred in windy conditions [27].

Besides meteorological conditions, other factors affecting the fire danger are the variety and extent of fuel (vegetation and dead organic material), the fuel moisture, and the topography (altitude, slope). The fuel loading of an area depends on land use (forest or cultivated area), the vegetation species, and the vegetation condition. Moisture content depends both on fuel size and atmospheric conditions. Thin dead materials, for example, needles, respond rapidly to moisture changes in the atmosphere. On the other hand, branches of large size and thick leaf layers maintain their moisture for several days after rain episodes, especially when calm conditions prevail and the saturation vapor pressure deficit is low [52]. Topography plays an important role in the initiation and spread of forest fires. The altitude affects the vegetation period through temperature and moisture changes in the atmospheric environment and the groundwater supply of the plants. During Mediterranean summers, green vegetation is restricted to higher altitudes. Green vegetation contains sufficient moisture and therefore prevents fire initiation and retards fire spread [52]. In upslope firs, the flame tilts over the potential fuel, thereby increasing radiation

TABLE 26.1 Forest Fires Frequency and Propagation Velocity in Greece according to Relative Humidity

Relative Humidity (%)	Forest Fires Frequency and Propagation Velocity
>50–60	Small number of incidents that cannot be spread with low wind speed
40–50	Low fire propagation velocity in thin fuel
31–40	The velocity increases per 1.5 times
26–30	The velocity doubles
16–25	The velocity triples creating dangerous situations

and more significantly causing direct flame contact. Indeed, the steeper the slope, the closer is the fuel exposed to the flames [52]. In no-wind conditions, even a moderate slope of 20% doubles the propagation velocity compared to a similar fire on a plane surface [32].

In summary, weather conditions are crucial for forest fires. Drought periods followed by dry and hot winds blowing from arid continental interiors over a period of days create a cumulative heating and drying effect on the vegetation. Furthermore, these are also the atmospheric conditions, which promote dry lightning storms that are a frequent ignition source [49].

26.3.3 Causes and Factors of Forest Fires

It is very important to know and study the principal causes of forest fires, for the purpose of understanding the phenomenon and taking action aimed at preventing and contrasting the fires themselves. It is possible for the causes of forest fires to differ from one area to another due to environmental factors, such as vegetation type, lightening frequency, climatic conditions, as well as anthropogenic activities. As a result, it is indispensable to gather and examine reliable data in order to identify and comprehend the possible causes of a forest fire and implement appropriate prevention measures. In Greece, the causes of wildfires are classified into three categories: (1) wildfires caused by natural causes, (2) wildfires caused by human activities, and (3) wildfires caused by dubious unknown reasons.

As previously mentioned, only the smallest percentage of fires can be considered to be natural, that is, caused by lightening, sparks, volcanic eruptions, etc. Forest fires attributable to anthropogenic activities are divided into those that are evoked randomly, or on purpose, such as arsons. Randomly evoked wildfires are caused either by negligence or accidents. Fires by negligence, or for involuntary reasons, are caused by human behavior, which is not aimed at the specific desire to create damage. Such fires are usually caused by cigarette stubs or matches, agricultural and forestry activities, such as clearing of uncultivated land, clearing of plant residue, burning of stubble, renewal of pastures or camping, tourist activities, military maneuvers or shooting exercises, bad maintenance of electrical lines or breakage or falling of wires, and illegal fires. Accidental causes are those that do not depend directly on anthropogenic action, whether by negligence or arson, even if referable to the presence of activities of people on the territory. This category includes fires caused by sparks that originate from friction of the breaking devices of trains against tracks, the variation of tension on electrical lines and from the breakage and fall of high tension wires, car crashes, and sparks from agricultural machinery.

Fires by arson are considered to be the deliberate will to set a fire with the intent of causing damage to the environment and to materials. The motives for arson can be grouped into categories, such as profit-seeking, manifestations of protest, resentment or insensitivity toward forests, as well as dubious causes. In the first category, fires are caused either by the creation or renewal of pastures at the expense of forests or by the will to regain agricultural terrain for cultivation or to activate funding from bodies such as the European Union, through legislation, which can attract a premium from the removal of vegetation for the purpose of agricultural cultivation. Another motive observed is the removal of vegetation for the purpose of land reclassification to urban land, which attracts a significantly higher selling price. In the second category, fires are caused either as vengeance or retaliation against the public administration, or by conflicts between or revenge against owners as protest against limitations imposed in conservation areas or from fun or games by a minority with the intent of devaluing tourist areas. Dissatisfaction, social dissent, behavioral disturbances (pyromania and mythomania), or matters connected to political contrast and terrorist acts have also been identified. The causes of forest fires in Greece and their percentage contribution for the period 1985–1997 are shown in Table 26.2.

26.3.3.1 Factors Affecting Forest Fires

The spread of forest fires varies based on the flammable material volume and its vertical arrangement. For example, fuels uphill from a fire are more readily dried and warmed by the fire than those downhill; yet, burning logs can roll downhill from the fire to ignite other fuels. Fuel arrangement and density are

TABLE 26.2 Causes of Forest Fires in Greece for the Period 1985–1997

Category of Cause	Contribution (%)
1. Negligence	
1.1 Cigarettes stubs or matches	14.0
1.2 Burning of stubble	21.1
1.3 Military shooting exercises	0.6
1.4 Trains and electrical lines	0.4
1.5 Sparks from machinery	2.7
1.6 Overheating	2.5
1.7 Bees smoking	0.6
1.8 Campers	1.5
1.9 Burn of wastes and other causes	5.0
1. Sum of causes due to negligence	48.4
2. Arsons	26.2
3. Natural causes	2.1
4. Dubious or unknown causes	22.5

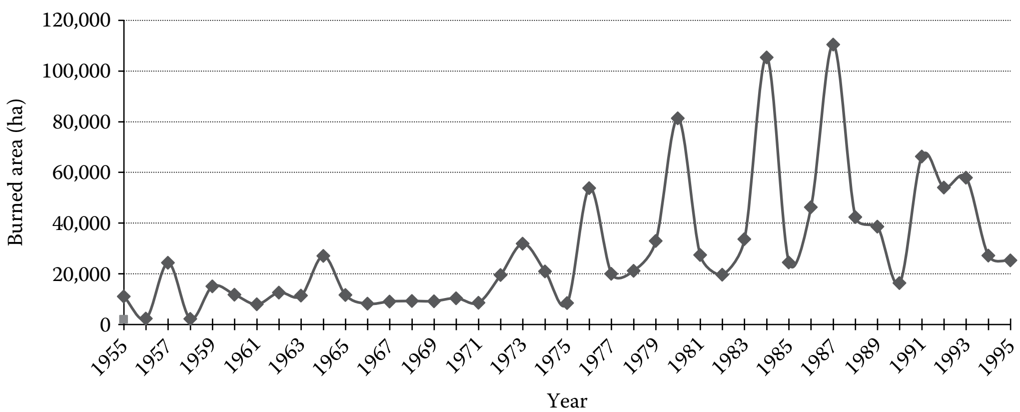

FIGURE 26.5 Burned area in Greece from forest fires (1955–1996).

governed in part by topography, as the land's shape determines factors such as available sunlight and water for plant growth. Forest fires in Greece have shown a significant increase during the last 25 years. The sum of burned forest areas per type (fully covered and partially covered forested areas, pastures) and as a sum for the period 1955–1996 are depicted in Figure 26.5.

26.4 Forest Fire Mitigation

26.4.1 The Wildfire Mechanism

A wildfire front is the portion sustaining continuous flaming combustion, where unburned material meets active flames, or the smouldering transition between unburned and burned material [39]. As the front approaches, the fire heats both the surrounding air and woody material through convection and thermal radiation. First, wood is dried as the water is vaporized at a temperature of 100°C. Next, the pyrolysis of wood at 230°C releases flammable gases. Finally, the wood can smoulder at 380°C or, when heated sufficiently, ignite at 590°C [38]. Even before the flames of a wildfire arrive at a particular location, the heat transfer from the wildfire front warms the air to more than 800°C, which preheats and dries flammable materials, causing them to ignite faster, allowing the fire to spread [16,36]. High-temperature and long-duration surface wildfires may encourage flash over or torching, which is the drying of tree canopies and their subsequent ignition from below. Wildfires have a rapid forward rate of spread when burning through dense, uninterrupted fuels. They can move as fast as 10.8 km/h in forests and 22 km/h in grasslands. Wildfires can advance tangential to the main front to form a flanking front, or burn in the opposite direction of the main front by backing.

26.4.2 Suppression

Wildfire suppression depends on the technologies available in the area in which the wildfire occurs. In developing countries, the used techniques can be as simple as throwing sand or beating the fire with sticks or palm fronds, whereas in developed countries, the suppression methods vary due to increased technological capacity. The key to controlling and suppressing a forest fire is getting manpower and equipment to the scene as quickly as possible. During the evolution of the fire, as information from the field and data from different sources (e.g., weather and satellite maps) become available, the firefighting strategy can be modified from the first-response plan [5]. It would be an understatement to say that the sooner a fire is reported, the quicker it can be extinguished. The instant a fire report comes in, a number of key questions need to be answered in order to initiate a suppression strategy: location, accessibility, as well as the size and category of the fire are all-important parameters. It is important to point out that total fire suppression is no longer an expectation. Nonetheless, the majority of wildfires are often extinguished before they get out of control. While more than 99% of the 10,000 new wildfires each year are contained, escaped wildfires can cause extensive damage. Worldwide damage from wildfires is in billions of dollars annually [20].

Drought conditions force firefighters to travel longer distances to obtain water, which results in more expense and usually greater fire damage. Often, an aircraft is flown over a reservoir to fill attached scoops; however, under drought conditions, as reservoir depths decrease and sources dry up, this is more challenging. Ideally, to combat the increased distances, more aircrafts should be employed, thus maintaining the volume of water available for extinction with respect to time. To expedite the swift location of potential sources, the updated surface water availability needs to be incorporated into a dynamic geographic information system (GIS) layer, thereby guiding crews to the closest and most productive sources within a commutable distance of the fire in a near real-time protocol. When sufficient water is not available, flame retardants can be very successfully employed. Flame retardants are used to help slow down wildfires, coat fuels, and lessen oxygen availability as required by various firefighting situations. They are composed of nitrates, ammonia, phosphates, and sulfates, as well as other chemicals and thickening agents [26]. The choice of whether to apply a retardant depends on the scale, location, and intensity of the wildfire. Flame retardants are frequently employed to reach inaccessible geographical regions, where ground firefighting crews are incapable to reach a wildfire or in any occasion where human safety and structures are endangered. In certain instances, fire retardants may also be applied ahead of wildfires for protection of structures and vegetation as a precautionary fire defense measure. Other methods commonly employed include bulldozers or fire breaks, which fundamentally remove the wood that serves as fuel for advancing wildfires. Firefighters also fight fire with fire by purposefully burning small bands of forest, to remove fuel from an uncontrolled wildfire. Because these smaller, deliberate fires, also known as backfires, are controlled and of lower heat, they can be extinguished easily. Firefighters also use other barriers, such as roads to contain a burn, by burning trees near a road and increasing the distance, as the fire would have to jump to keep burning. Despite these techniques, water does still play a key role in protecting buildings and human structures.

26.4.3 Planning Control

Wildfire prevention refers to preemptive methods of reducing the risk of fires, as well as lessening its severity and spread. Effective prevention techniques allow supervising agencies to manage air quality, maintain ecological balances, protect resources, and to limit the effects of future uncontrolled fires [53]. Firefighting policies may permit naturally caused fires to burn to maintain their ecological role, so long as the risks of escape into high-value areas are mitigated. On the other hand, prevention policies must consider the role that humans play in wildfires.

Other than reducing human infractions, only fuels may be altered to affect future fire risk and behavior. Wildfire prevention programs around the world may employ techniques such as wild land fire use and prescribed or controlled burns. Wild land fire refers to any fire of natural causes that is monitored but allowed to burn.

Vegetation may be burned periodically to maintain high species diversity and frequent burning of surface fuels limits fuel accumulation, thereby reducing the risk of crown fires. Using strategic cutting of trees, fuels may also be removed in order to clean and clear the forest, prevent fuel buildup and create access into forested areas. Multiple fuel treatments are often needed to influence future fire risk, and wildfire models may be used to predict and compare the benefits of different fuel treatments on future wildfire spread. Nonetheless, controlled burns are considered by many agencies to be the most effective treatment for reducing a fire's rate of spread, fire-line intensity, flame length, and heat per unit of area. Effective fire management requires the administration of fuels across large areas in order to reduce future fire size and severity.

26.4.4 Protection from Forest Fires

In order to have an integrated forest fire protection system two kinds of measures are needed: prevention measures and suppression measures. Prevention is the key in helping to reduce the number of human-caused wildfires. The programs of prevention are related with all the activities that aim in the minimization of impacts of forest fires. The various techniques that can be used for reduction of anthropogenic fires fall into two general categories, namely, to reduce danger risk and to manage it. The danger is related to the outbreak of fire, whilst the reduction of the possibility of having a wildfire ignited is highly correlated with the increase of public awareness. A series of measures can be employed, such as the use of publicity campaigns on local and national radio or television channels, and in today's age of social media, messages can reach far and wide via this channel of diffusion. Likewise, the application of laws on fires is potentially a useful preventive approach. Education and the application of legislation are useful preventive measures when the fires are results of ignorance, carelessness, or malice. Other measures in order to prevent fire ignition and spread include the creation of fire breaks or fuel breaks or replacement of flammable fuels, such as conifers, by nonflammable fuels, for example, broadleaves, around and across regions of high danger, such as dumps, camps, road, and railway network. Despite the high cost of creating and maintaining firebreaks, many countries continue to use this method for the reduction of fire risk. The use of different types of vegetation cover is considered a very important measure in order to prevent large fires. Moreover, the development of a network of meteorological stations is indispensable to assist forest fire danger forecast and contribute to daily fire risk mapping.

In most instances, where initial reports are unclear or when a fire is in a remote area, the evaluation is carried out from the air. The method of transporting personnel to a fire site varies depending on the terrain and its accessibility. Ground transport usually relays firefighters to within a reasonable driving distance of a wildfire. Where no road access is available, the suppression is more focused on aerial strategies.

In recent years, despite the increasing expenses with regard to suppression mechanisms, a more efficient organization of confrontation, which focuses on fire prevention, has developed. Nevertheless, in many countries, the abundance of rural regions and the concentration of the population in urban areas, along with the ageing of farmers and subsequent abandonment of lands, have had a significant effect in the accumulation of fuel matter. This requires significant changes in the configuration of the forest policy, requiring the preventive confrontation of fires. The said policy must be focused on the use of technological innovations and the implementation of pilot programs and studies. Hand in hand, the improvement of existing databases and infrastructure, with a thorough investigation of causes and cost–benefit analysis are also critical.

26.4.5 Forestry Management against Fires

Although some ecosystems rely on naturally occurring fires to regulate growth, many ecosystems suffer from too much fire, such as the chaparral in southern California. The increased fire frequency in ordinarily fire-dependent areas has upset natural cycles, destroyed native plant communities, and encouraged the growth of fire-intolerant vegetation and nonnative weeds [30,64]. Invasive species, such as *Lygodium microphyllum* and *Bromus tectorum*, can grow rapidly in areas that were damaged by fires. Since they are highly flammable, they can augment the future risk of fire, creating a positive feedback loop that increases fire frequency and further destroys native growth. Wildfires generate ash, destroy available organic nutrients, and cause an intensification in water runoff volume due to interstitial space blocking and erosion of other nutrients that can give rise to flash floods. Wildfires can also have an effect on climate change, increasing the amount of carbon released into the atmosphere and inhibiting vegetation growth, which affects the overall carbon uptake by plants.

26.4.5.1 Effective Land Use Planning to Mitigate the Propagation of Fire

Fire management is often very expensive and it is not uncommon for suppression operations for a single wildfire to exceed costs of $1 million in just a few days. The United States Department of Agriculture allotted $2.2 billion for wildfire management in 2012 [54]. Although fire suppression offers many benefits to society, other options for fire management also exist. While these options cannot completely replace fire suppression as a fire management tool, alternatives can play an important role in overall fire management and can consequently affect the costs of fire suppression. Current approaches to fire management are an almost complete turnaround compared to historical approaches. Indeed, it is commonly accepted that past fire suppression, along with other factors, has resulted in the larger, more intense wildfire events that are seen today [58]. In economic terms, expenditures used for wildfire suppression in the early twentieth century have contributed to increased suppression costs, which are being realized today. As is the case with many public policy issues, costs and benefits associated with particular fire management tools are difficult to be accurately quantified. Ultimately, costs and benefits should be weighed against each other on a case-by-case basis in planning wild land fire management operations.

26.5 Forest Fire Monitoring

The operational monitoring and mapping of the burned areas are very important aspects in dealing with emergency situations and the quantitative estimation of the affected area. The assessment of the damaged areas can provide valuable information to the authorities and insurance companies [12]. The contribution of new technologies, such as remote sensing, photogrammetry, and GIS, in monitoring wildfires is very significant.

26.5.1 Remote Sensing as a Tool for Monitoring Forest Fires

The possibility of using satellite data for land cover classification, vegetation monitoring, and mapping has been a research subject for several decades. By directly observing the plant's radiometric response, it is possible to record the canopy reaction to environmental stresses and constraints directly and in real time [8,52].

Remote sensing is a useful tool for providing information before, during, and after the forest fires. Remotely sensed data and techniques have been used to detect active fires and extract the extent of the burned area during the fire [8]. The methods usually applied are based on the thermal signal generated by flaming or smouldering combustion [21,25,31,34] and the daily fire growth [6]. The use of contextual algorithms [18] can improve the detection of active fires.

26.5.2 Early Warning Systems for Wildfire Detection and Damage Mitigation

Fast and effective detection is a key factor in wildfire fighting. Early detection efforts were focused on early response, accurate results in both daytime and nighttime and the ability to prioritize fire danger [1]. Fire lookout towers were used in the United States in the early twentieth century and fires were reported using telephones, carrier pigeons, and heliographs. Aerial and land photography using instant cameras were used in the 1950s until infrared scanning was developed for fire detection in the 1960s. However, information analysis and delivery were often delayed by limitations in communication technology. Early satellite-derived fire analyses were hand drawn on maps at a remote site and sent via overnight mail to the fire manager. Currently, public hotlines, fire lookouts in towers, and ground and aerial patrols can be used as a means of early detection of forest fires. Nonetheless, accurate human observation may be limited by operator fatigue, time of day and year, as well as geographic location.

Near real-time systems have gained ground in recent years as a possible resolution to human operator error, although detection by the camera systems has been reported to be slower and less reliable than reports by a trained human observer. Satellite and aerial monitoring through the use of planes, helicopter, or drones can provide a wider view and may be sufficient to monitor very large, low-risk areas. These more sophisticated systems employ GPS and infrared or high-resolution visible cameras to identify and target wildfires [15]. Satellite-mounted sensors, such as Envisat's advanced along-track scanning radiometer and European remote sensing satellite's along-track scanning radiometer, can measure infrared radiation emitted by fires, identifying hot spots greater than 39°C [16]. The National Oceanic and Atmospheric Administration's Hazard Mapping System combines remote sensing data from satellite sources, such as geostationary operational environmental satellite (GOES), moderate-resolution imaging spectroradiometer (MODIS), and advanced very high resolution radiometer (AVHRR) for detection of fire and smoke plume locations [37]. However, satellite detection is prone to offset errors, anywhere from 2 to 3 km for MODIS and AVHRR data and up to 12 km for GOES data [46]. Satellites in geostationary orbits may become disabled, and satellites in polar orbits are often limited by their short window of observation time. It should be noted that cloud cover and image resolution may also limit the effectiveness of satellite imagery.

26.5.3 Forecasting and Risk Assessment

The development of fire-weather forecasting systems is an essential tool in the framework of forest fires prevention planning. In this context, the role of the National Meteorological services as providers of specific services is decisive. A hierarchy of such services has been presented [47], ranging from fire-weather warnings produced by central meteorological offices to fire-weather forecasting services provided to personnel at the scene of existing forest fires [4]. Forest fire risk assessment is an important component of every fire suppression organization, since it allows for proper fire prevention planning and is economically judicious, since it requires relatively reasonable investments if compared to the costs of nonscientifically based suppression on active wildfires [11]. As mentioned previously, remote sensing is a useful tool for providing information before, during, and after the forest fires [17]. The contribution of remote sensing to the prediction of a sensitive area can be achieved through the estimation of indices used for fire risk assessment models. These indices in combination with meteorological parameters and other fire risk assessment indices can be employed for forecasting wildfires.

26.5.3.1 Fire Assessment Indices

One of the most widely known fire assessment indices is the fire weather index (FWI). FWI provides numerical rating of relative wildland fire potential in a standard fuel type on level terrain. It consists of six components that individually and collectively account for the effects of fuel moisture and wind on fire behavior [11]. The amount of moisture that air holds depends on air temperature, which also affects the dehydration processes of the potential fuel. Investigation of fire statistics for air temperature and fire occurrences in Greece showed that 68.5% of fires occur between 21°C and 30°C. A combination of the latest two meteorological parameters in the form of probability tables or indices is used in the fire risk assessment by several forest services [35]. Another index used for risk assessment is called Angström's (*I*) index [27] and is given by the following equation [52]:

$$I = \frac{RH}{20} - \frac{27 - T}{10} \tag{26.1}$$

where *T* and *RH* are air temperature and relative humidity, respectively. When *I* is greater than 4, no fires are expected and when *I* is less than 2, meteorological conditions are very favorable for fire initiation [52]. The type of vegetation is also very significant. Some species are more vulnerable to fire and others are highly flammable, increasing the risk for fire ignition. A fire initiation risk map for Greece, based on the type of vegetative cover, is depicted in Figure 26.6.

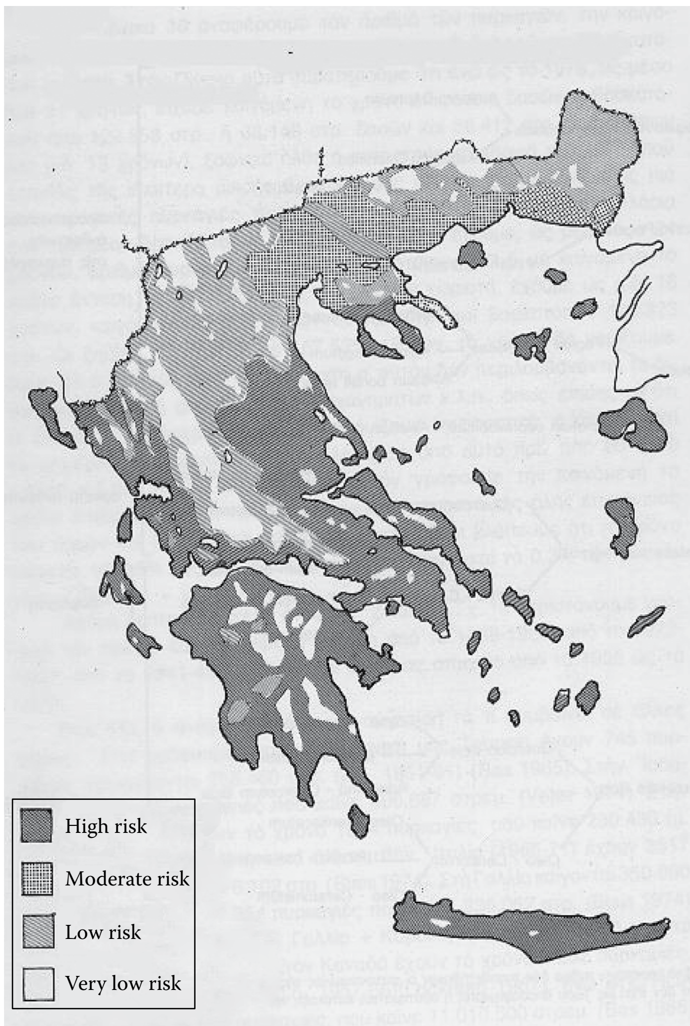

FIGURE 26.6 Fire initiation risk map for Greece based on the vegetative cover.

26.6 Forest Fires Assessment

The delineation of the burned area has been the subject of research, applying methodologies on images of different spatial and temporal resolution, multithresholding algorithms and different channel combinations. Such techniques involve the location and estimation of the aerial extent by subtracting NOAA/AVHRR normalized difference vegetation index (NDVI) images before and after the forest fire [7,8,28,29,52] or using maximum value composites from NDVI [19]. The *NDVI* is calculated as follows:

$$NDVI = \frac{NIR - RED}{NIR + RED} \tag{26.2}$$

where
RED = *DN* values from *RED* band
NIR = *DN* values from near-infrared band

Algorithms have been developed for monitoring the burned areas combining *NDVI* [43] or the global environment monitoring index (GEMI) [2,3] with multitemporal brightness temperature differences.

The delineation of the burned area depends on the type of burned vegetation, the soil type, the time interval after the fire and the extent of the fire (totally or partially burned). In all these cases, the spectral signatures of the land cover objects do not have a characteristic pattern. This makes the precise identification of the burned area difficult, especially whenever the resulted area is needed for operational use and ground truth data are not available. After the cease of a fire, significant reduction of the vegetation is expected and values corresponding to complete lack of chlorophyll elements are an indication of the burned area. Vegetation indices are an acceptable technique for identifying vegetation changes. NDVI is a quick and efficient way for fire monitoring [12]. Among other vegetation indices, the NDVI is the least affected by topographic factors and the difference gives the best indication of vegetation change [33]. The ground resolution of the remotely sensed data ranges from 1 m to more than 1 km. The choice of the appropriate resolution depends on the information desired. High-resolution images provide more information of the study area but result in a large amount of data. On the other hand, meteorological satellites provide low-resolution data but higher temporal resolution, appropriate for monitoring and operational requirements in forest fires.

The methods usually developed for mapping the burned areas are based either on the thermal signal or the use of an index or an algorithm utilizing both (thermal and index) information. When a technique is applied for operational purposes, the accuracy of the derived map needs to be known, in order to increase the credibility of the extracted results. It is thus appropriate not only to have on hand a quick and efficient method, but also to reach an acceptable degree of accuracy, which can be achieved by this method, thus indicating its usefulness as well as that of the sensor from which the data are obtained.

The accuracy of the resultant damaged area derived from Landsat TM and the shortcoming of natural resources satellites with higher spatial resolution is expected to be higher compared to that obtained from NOAA/AVHRR. However, operational needs impose the near real-time estimation of the burned area. This can be achieved only by using meteorological satellite data from NOAA/AVHRR, which has the appropriate temporal resolution and can be readily available by local receiving stations. In this case, knowledge of the corresponding agreement of NOAA/AVHRR-derived area extent with that achieved by Landsat TM is necessary for the initial assessment of burned areas in near real time.

26.6.1 NDVI for Assessment and Mapping Burned Areas: Case Study

The current application deals with the forest fire of July 21–24, 1995, in Penteli, Greece [8]. The technique applied for mapping the affected areas is based on the NDVI derived from both NOAA/AVHRR and Landsat TM satellite data. The study attempted to assess the agreement of the NDVI, extracted by

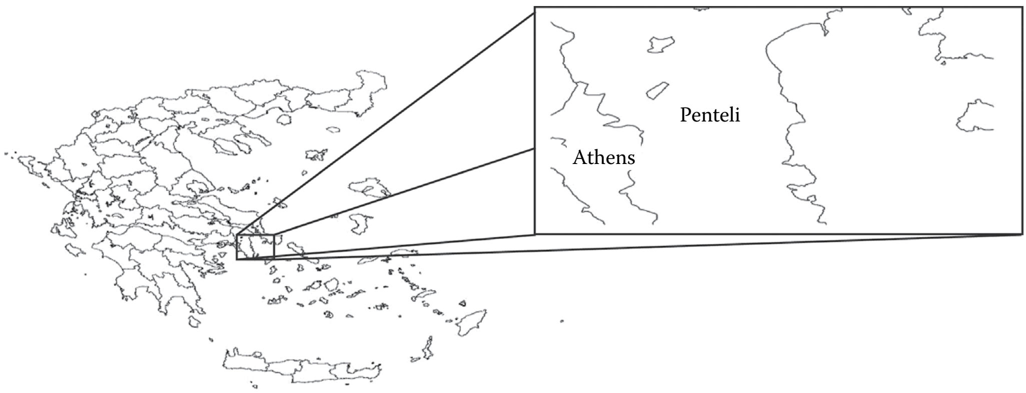

FIGURE 26.7 The study area is located in Penteli, Athens Greece.

NOAA/AVHRR and evaluate that by comparing with the NDVI produced with Landsat TM data, delineating the burned areas. A delineation and quantitative estimation of the affected areas are presented. Also, the results derived from the application of the dataset are compared with a reference map created by the optical interpretation of a Landsat TM color composite image, to indicate the credibility of the NOAA data for operational needs in forest fires.

The study area comprises the Penteli area, northeast of Athens, Greece (Figure 26.7). A forest fire, during July 21–24, 1995, destroyed a forested area of about 63 km^2. Satellite data before and after the initiation of this small-scale fire was meticulously examined. The dataset used for this study was part of a series of daily NOAA/AVHRR and two Landsat TM images acquired before and after the forest fire. From the NOAA/AVHRR dataset, two images were selected, one of July 20, 1995, and the second of July 25, 1995.

The spectral signatures of green vegetation are defined by the electromagnetic radiation. Chlorophyll absorbs the radiation at 0.62–0.7 μm and reflects it in near-infrared 0.74–1.1 μm. By observing directly the plants' radiometric response, it is possible to record the canopy reactions to environmental stresses and constraints directly and in real time [8]. This leads to the concept of NDVI, which is an indication of the amount of green vegetation. The NDVI is given by the formula $NDVI = (Ch_2 - Ch_1)/(Ch_2 + Ch_1)$ where Ch_1 and Ch_2 are the radiances of the first two channels of NOAA/AVHRR or, alternatively, bands 3 and 4 of Landsat TM. The NDVI maps were derived from both Landsat TM and NOAA/AVHRR images. The NOAA/AVHRR images were registered to the Landsat TM image and resampled to 30 m, to allow multitemporal analysis. The agreement assessment of the NOAA/AVHRR NDVI images requires the use of a reference map defining the burned and nonburned areas. Additionally, a method for detecting the burned areas by means of NDVI requires the use of multitemporal images. The methodology that followed involved the selection of a color composite to assist the visual interpretation, discrimination of the burned areas, and the agreement assessment of the retrieved results [12].

Figure 26.8a and b show color composites of the Landsat images before and after the forest fire, respectively. The burned areas appear as dark, whereas vegetation areas appear lighter; the sea is to the right of the map, and the bare land, clouds, and urban areas as white [12]. As expected, Landsat TM described with more details the burned area. It is worth mentioning that because of the pixel resolution associated with NOAA/AVHRR, it is not possible to determine spatial variations, thus the possible unburned patches in the area cannot be identified. Furthermore, it seems that at the edges of the burned area, where the areas are not totally burned, NOAA/AVHRR identifies them as burned or does not recognize them at all [12]. The area extent derived during the fire and the delineation of the burned area using the NDVI technique described in this case study reinforce the utility of NOAA/AVHRR data for operational monitoring and assessment of the damaged area in near real time with a high degree of accuracy.

Often, the burned areas need to be assessed by mapping their extent and estimating the damage in near real time. In this study, NDVI abrupt changes before and after the fire were the basis for examining the

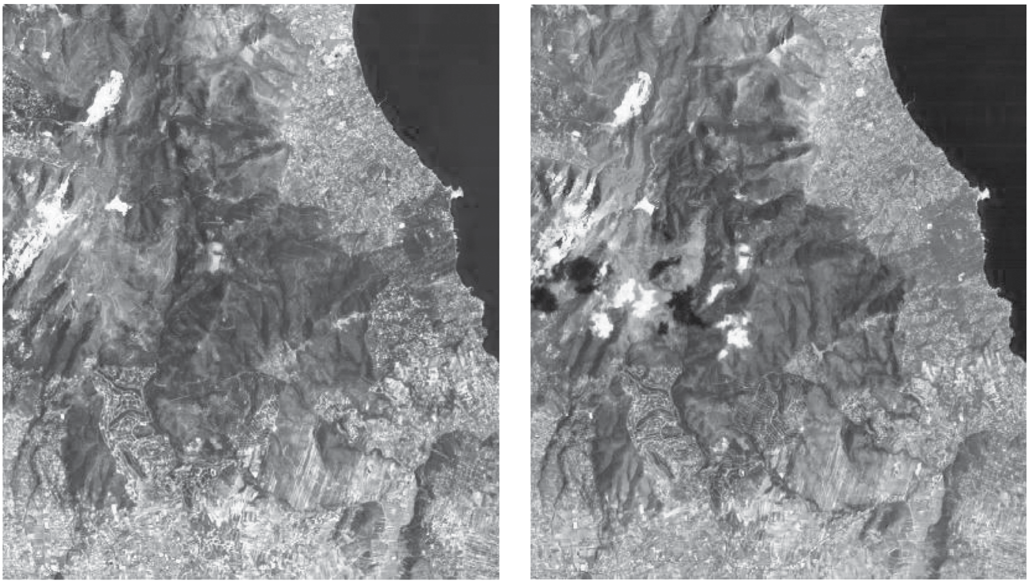

FIGURE 26.8 Landsat TM color composites images (7,4,1) before (a) and after (b) the forest fire in Penteli, Greece. This band compilation highlights the burned area. (From Domenikiotis, C. et al., *Int. J. Remote Sens.*, 23, 4235, 2002.)

study area and proved to be a very powerful tool. The magnitude of such changes depends on the amount of burned area per pixel, the vegetation density, and the dominating species [12]. Comparing the extracted areas with the reference map, it was found that damage assessment using satellite NOAA/AVHRR data is an efficient way for the detection of burned areas. Lastly, it should be emphasized that although the overall agreement of both datasets was similar, the Landsat TM was much more accurate when it came to the estimation of the burned areas only. Additionally, comparison between the identified burned areas from both sensors showed that Landsat TM can vary spatially without having the raster appearance of NOAA/AVHRR [12].

26.6.2 The Response of Soils to Rainfall following a Fire

As previously commented, fire effects that occur at the vegetation–soil interface can result in altering overland flow and the infiltration of water. Infiltration rates are affected by collapsing soil structure and reduced porosity. Ash and charcoal residues clog pores, and raindrops can compact soft soil, resulting in the greater reduction of porosity. Furthermore, in the case of fires involving trees, such as spruce, resin containing turpentine and resin acids, forms a hydrophobic layer on the soil surface. In consequence, following a fire, rainfall intensity and duration can influence the quantity of sediment transported to a stream channel, which, when associated with a hydrophobic layer, can give rise to excessive sediment being carried to water courses and excessive land erosion.

26.7 Summary and Conclusions

Water shortage has become more pronounced over the last 50 years as a result of increasing population and per capita use increase in developed societies. In addition, agricultural practices and quality demands on the end products require larger volumes of water to facilitate irrigation. Accumulating to the aforementioned problems, the effects of climate change can give rise to climatic extremes of extended drought periods, which may potentially create conditions for combustion, that is, dry vegetation, air, and soil, leading to forest fires. To counter these effects and consequent combustion, the effective land and resource management strategies must be employed through forest fire mitigation and monitoring.

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27

Education Program for Drought

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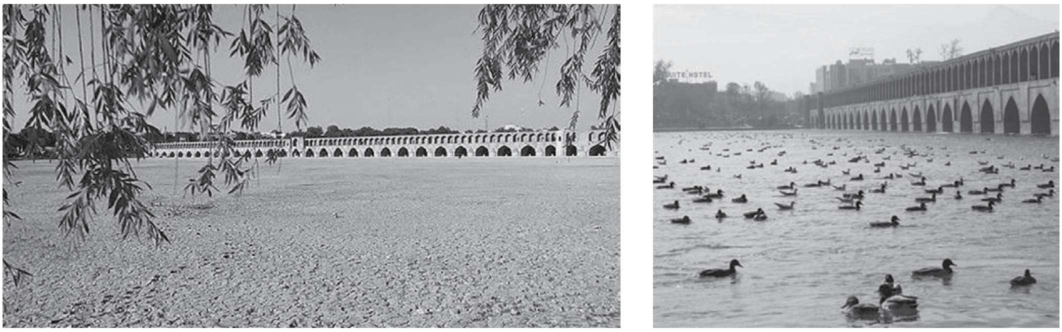
Abstract Currently, drought is regarded as a significant natural disaster. Moreover, drought planning, drought management, and prevention of its negative impacts are difficult. Drought and climate change have negative environmental impacts, leading to social and economic crises. Compensating for these negative impacts needs long-term planning and investment. The important strategy to minimize drought damage is identification of the drought phenomenon and planning for coexistence with it. In this regard, education, exchange of knowledge, knowledge transfer, knowledge management, and learning play a valuable role in drought management. The main objective of this chapter is to summarize the strategies of educational programs relating to drought. The development of network activities, linking schools and climate change, organizing events, using tourism and art as tools for knowledge transfer, and establishing museums are good examples for popularization of and education on drought, whether for children or adults.

27.1 Introduction

Drought as a natural disaster is a shortage in precipitation over an extended period, usually a season or more, resulting in lack of rain, causing adverse impacts on vegetation, animals, and/or people's living conditions. It is noteworthy that drought occurs in virtually all climate zones, from very wet to very dry. As an example, Brazil has about 12% of the total drinking water on the planet but nine million people from S. Paulo have been affected by drought since 2013, the worst in 80 years. Drought is a temporary aberration from normal climatic conditions, thus it can vary significantly from one region to another [40]. According to NOAA (National Oceanic and Atmospheric Administration), drought is commonly defined in three ways, which reflect various perspectives and interests: meteorological drought, agricultural drought, and hydrological drought. Obviously, countries are vulnerable to the social, economic, and environmental impacts of drought and climate changes. Nowadays, drought, global warming, and climate change are huge challenges to human lives. Climate change and drought not only have negative



(a) (b)

FIGURE 27.1 Zayanderood river landscape (a) before and (b) after drought, Isfahan, Iran.

impacts on biodiversity and human health but also change lifestyle patterns, energy consumption patterns, and rural and urban landscapes (Figure 27.1). Furthermore, economic activities such as agriculture, aquaculture, forestry, tourism, hotel management, etc. may be negatively affected by climate change and drought.

Lack of public awareness and support are key parameters that intensify the negative impacts of drought. In order to decrease the negative socioeconomic impacts of drought, the obligatory education system should provide people with the possibility to learn how to reduce the risks associated with drought. Under the United Nations Millennium Development Goals and the Water for Life Decade 2005–2015, one of the main duties of governments, schools, universities, and involved institutions is to raise awareness in the general public about issues such as water conservation, rain water harvesting techniques, water-related disease prevention, recycling used water to irrigate gardens or using it for toilet flush tanks in hotels, modifying irrigation systems, and adapting crop and grazing patterns.

The primary purpose of this study is to present a summary of strategies for popularization and public awareness about the consequences of drought and how to cope with it in everyday activities.

27.2 Educational Program and Drought

Education, as a lifelong process, is widely accepted as a fundamental prerequisite for the achievement of sustainable development. It is also recognized as a means of changing consumption and production patterns to a more sustainable path [17].

Since schoolchildren are the future generation of our planet, and the bridges between schools and homes, the first strategy that can be applied for popularization of the impacts of drought is organizing educational programs and workshops for children. Arranging a workshop entitled "Water efficiency" in primary and guidance schools of the Chaharmahal and Bakhtiari Province (Iran) is an example in this regard [58]. Moreover, the National Drought Mitigation Center has prepared some information that gives an overview of drought—the science, the impacts, and what people can do to prepare for drought—to teachers, high school students, and adults [39]. During the International Year of Water Cooperation 2013, proclaimed by the UN, the Portuguese Geoparks under the UNESCO Global Network of National Geoparks organized a school contest for local schools under the subject "Water that Unites Us" [48].

Furthermore, celebrating events such as the World Day to Combat Desertification (June 17), the World Environment Day (June 5), the World Water Day (March 22), the International Day of Forests and Trees (March 21), and Earth Day (April 22) is another strategy for popularization of drought and water scarcity. Since 1992 desertification has threatened Qeshm Island, the Natural Resources Department of Hurmozgan province has launched a propagation of the plant *Avicennia marina*. Annually, many of these species are planted in the sea forest region especially on March 5—the day of afforestation in Iranian culture.

The local governors, by encouraging locals to participate in the propagation of the plant *Avicennia marina* in the mangrove sea forest ecosystem, are creating supplementary income for locals [24].

Meanwhile, networks such as African Drought Risk and Development Network (ADDN) and Africa-Asia Drought Risk Management Peer Assistance Network (AADP) are providing a platform of cooperation and exchange between experts.

Establishing themed museums and exhibits for drought and water is the fourth solution for transferring knowledge from professional to public levels. Preparing materials and publishing books and manuals [4,5,9] are educational tools to combat drought. Obviously, access to media, such as television channels, magazines, public advertisements, and websites play a major role in public awareness; for instance, National Geographic Education produced some programs, such as: "Defining Drought"; "Causes of Drought"; "Impacts of Drought"; "Historical Droughts"; "Major Droughts in the Past Century"; Forecasting and Measuring Drought"; "Preparing for Drought" [36]. Besides, Drought Online as a web-based communication tool for the African Drought Risk and Development Network (ADDN) and Africa-Asia Drought Risk Management Peer Assistance Network (AADP), a site managed by the UNDP (United Nations Development Programme) and the UN-ISDR (United Nations International Strategy for Disaster Reduction) with the technical support of the FAO, offers easy access to a growing collection of drought risk reduction related resources and provides an avenue for continued dialogue and interaction among the interested network participants beyond geographical boundaries [18].

In addition, combining climate and earth sciences with recreational activities is another strategy for knowledge transfer and the preservation of our planet. Organizing photography workshops, trips and travel, and establishing a photo gallery on drought increase public knowledge about the impacts and causes of drought and water shortage. In this regard, the AADP organizes small-scale interregional knowledge exchanges such as study tours. These educational tours allow participants to learn from each other's experiences, expertise, and skills. It is worth mentioning that the first interregional study tour for drought was hosted by the Government of Kenya in October 2012 with the aim of fostering a partnership between China and drought-prone countries in sub-Saharan Africa.

The experiences show that NGOs (nongovernmental organizations) and private institutions are key components in knowledge sharing and education about drought in rural areas. For example, The Rural Education Program (REP) as a short-term program of the Foundation for Rural and Regional Renewal was established in 2002. The REP organized educational programs about the effect of drought on children living in rural and remote areas of Australia by volunteer teachers [54].

We draw attention to the fact that organizing conferences, meetings, and symposiums, at local and international levels, also provides opportunities for students, universities, companies, and public and private sectors to exchange knowledge on drought management. Mostly rural territories are members of the Global Geoparks Network, which now numbers 101 labeled areas under UNESCO, and organizes the Geoparks Conference annually. Since the II International UNESCO Conference on Geoparks held in the German city of Osnabrück in 2008, these conferences have included sessions on Natural Hazards and Climate Change. Geoparks are natural labs where drought and climate change processes are being explored through educational activities for raising awareness in local communities [45].

Forasmuch as drought and climate changes have a huge negative impact on some economic activities such as tourism, forestry, and agriculture, providing and publishing manuals by involving international experts in organizations such as UNEP (United Nations Environment Programme), UNDP (United Nations Development Programme), and FAO (Food and Agriculture Organization) can be an initial attempt to present guidelines for water conservation and reuse for people who are involved in those areas. The publishing of "Manual for water and waste management: what the tourism industry can do to improve its performance," by UNEP is an excellent example of sustainable tourism and knowledge transfer for improving performance of tourism in water management [32]. Additionally, World Tourism Day 2013 (September 27) was celebrated under the main subject "Tourism and Water: Protecting our Common Future," showing the importance of changing paradigms in the tourism industry.

27.2.1 Knowledge Management for Drought

According to the Oxford Dictionary [43], knowledge includes facts, information, descriptions, or skills acquired through experience or education. Knowledge is more comprehensive than sciences. It can be said that the knowledge to prevent drought not only comprises sciences such as geosciences, meteorology, natural resources, environment, watershed management, and water management but also includes empirical and practical experiences regarding consumption, management and saving of water, soil and harvesting management, and forestry industry management.

At present, the earth faces problems such as global warming, air and water pollution, soil salinization, overpressure on natural resources and environment, loss of biodiversity, international conflicts for the control of mineral deposits, unsustainable activities, unsustainable tourism, most of which has occurred due to a shortage of strategies for the popularization of water conservation, water consumption, and sustainable water management, as well as the weakness of practical strategies for knowledge sharing for drought, and unsustainable performances of governments at diverse levels according to their economic benefits.

Construction, embodiment, and dissemination are elements for managing and sharing knowledge [16]. Some authors [33,41,52] introduce knowledge management as a skill of creating value from intangible assets. It is evident that earth sciences comprise complex and intangible scientific concepts such as drought and the effect of drought on socioeconomic living, which are not user-friendly for the public in general and schoolchildren in particular. In recent decades, governments, private sectors such as NGOs, education institutions, and museums have striven to make tangible products from the intangible concepts and ideas in earth sciences and water management. In addition, they have attempted to transfer knowledge of drought from technical to public levels.

Knowledge transfer occurs in four ways: (1) tacit to tacit, achieved through a process of socialization via meetings and team discussions; (2) tacit to explicit, externalized through brainstorming and the use of developers; (3) explicit to explicit, by moving knowledge around a network from one organization to another, which is relevant for destinations; and (4) explicit to tacit, taking explicit knowledge such as a report and generating new ideas. Explicit knowledge is transferable and easier to codify than tacit knowledge [41]. Thus, it is usually the focus of an organization's interest and is found in such forms as documents, databases, and files. Furthermore, tacit knowledge and its owners are difficult to manage [11]. This is further illustrated in the following examples. For instance, organizing the High-level Meeting on National Drought Policy (HMNDP), in Geneva, Switzerland, in 2013, and the International Symposium on Integrated Drought Information Systems, in Casablanca, Morocco, in 2011 are examples for tacit to tacit knowledge transfer (e.g., through simply exchanging ideas) or tacit to explicit (e.g., registering those ideas in a systematized way in the proceedings).

27.2.2 Museum and Drought

According to The International Council of Museums' definition: "A museum is a nonprofit making, permanent institution in the service of society and of its development, and open to the public, which acquires, conserves, researches, communicates and exhibits, for purposes of study, education and enjoyment, material evidence of people and their environment" [3]. Therefore, it can be said that museums, and especially themed museums, are tools for education and learning. Ambrose and Paine [3] noted that the emphasis of museums has moved from education, which implies museums teaching things to children, to learning, which implies individuals of all ages using the museum for their own benefit. They argued that learning is not just about facts; it includes experiences and emotions as well. Generation and use of new knowledge to feed innovation and product development play a pivotal role in provision of drought and desertification. For example, the combination of earth and water sciences with tourism and museology can be a strategy for popularization of the causes of drought, which are easily understood, but hard to prevent. Hence, organizing events and establishing museums and exhibitions for drought can be a strategy for knowledge transfer of the negative impacts of drought on earth and human life.

During the period 2006–2010, the National Museum Australia organized an educational program entitled "Investigating drought – its causes, impacts, management." In this educational program, students explored the causes and effects of drought and drought management [37]. Moreover, Museum Victoria (Australia) organized a workshop regarding Drought and Water Conservation, the motto of the educational program being "Don't Waste Water, turn off taps" [35].

In addition, in the United States, the Great Plains Art Museum at the University of Nebraska-Lincoln opened a new exhibit of drought-related artwork .The exhibition was a special event during the 2014 Great Plains Symposium that showed the effects of drought on the life, cultures, and landscapes of the Great Plains. The symposium created an opportunity for scientists, scholars, agency officials, farm leaders and others from across the spectrum of disciplines and organizations to share their knowledge and expertise about drought in the Great Plains [57]. Besides climate change and drought-related museums, water museums play an important role in water conservation and management. A modern water museum established in Arnhem (the Netherlands) explains to visitors all about freshwater. The museum includes the following sectors: water laboratory, water world exhibits, Water Information Centre, and Water Cinema. The museum organizes educational programs in the water laboratory for children between the ages of 6 and 12 to do all sorts of experiments with water (Figure 27.2). In the Water Cinema and exhibits, visitors are also educated about water management and the importance of water in other parts of the world (Figure 27.3) [53].

The establishment of Sadabad Water Museum (Tehran) and the Water Museums in Isfahan and Yazd, Iran, constitute good examples. These museums exhibit water storage and include a lot of interesting information about the *qanat* water distribution system. Qanat is one of a series of well-like vertical shafts,

FIGURE 27.2 Water laboratory for children in Arnhem (the Netherlands).

FIGURE 27.3 Water museum in Arnhem (the Netherlands); exhibit on water and drought in other parts of the world.

connected by gently sloping tunnels. Qanats create a reliable supply of water for human settlements and irrigation in hot, arid, and semiarid climates.

It can be concluded that museums can play a valuable role in popularization of scientific data and technical information, providing an understanding of knowledge about drought and water.

27.2.3 Networking and Educational Program for Drought

According to Hjalager's definition [28], collaborative structures and authority systems belong to the category of management innovation; thus, nowadays, collaboration in the form of clusters, networks (horizontal or vertical), or forums are recognized as innovation in management, especially in the exchange of knowledge, experiences, and sciences.

Knoke and Kuklinski [31] explained the networks as "a specific type of relation linking a set of persons, objects or events." Porter [44] described clusters as "geographic concentrations of interconnected companies and institutions in a particular field, linked by commonalities and complementarities." Agencies organized at the same level are classified as horizontal networks, while relationships between different levels of management (local, regional, and national) are formed in vertical networks [27].

The experiences of Jennings and Zandbergen [29] illustrated that individual stakeholders contribute less to environmental sustainability than networks of agents. Networks of collaboration are key components in environmental management [47]. In addition, networks increase the effectiveness of volunteers in activities [50].

The experiences of Dredge [19] in Lake Macquarie (Australia) illustrated that in network activities, stakeholders can have membership of more than one network and stakeholder powers, roles, interactions, and functions may become stronger. Moreover, collaboration in the form of a network creates opportunities for communication, for dialogue, for the development of new ideas, and for the translation of ideas into practice. ErkuŞ-Öztürk and Eraydin [23] noted that collaborative work in the form of networking and local collaboration in Antalya (Turkey) has provided more protection than individual organizations.

The earlier definitions show that establishment of local, national, and international networks are one of the key components for a knowledge-sharing platform on climate change and drought. The establishment of the Climate Change Knowledge Network (CCKN) and the Climate Action Network (CAN) constitute good examples. The CCKN and the CAN are tools for transferring expertise, experience, and perspectives from research institutes in developing and developed countries active in the area of climate change. They provide a forum for research on the issues of international climate change and drought. It can be said that these two networks work to promote government and individual activities to limit human-induced climate change to ecologically sustainable levels.

Additionally, Australia's rural areas, with the intention of solving challenges in social, economic, and environmental terms (irrigation and dryland salinity, soil erosion, soil acidity, water quality, and pest animals and plants), established local networks named the Landcare Network, the Holbrook Network, and the Woady-Yaloak Network [50].

DesertNet International is a global network that includes experts from almost 50 different countries. DesertNet International strives to generate and enhance knowledge and understanding of the biophysical and socioeconomic processes of desertification. Moreover, this network supports any mechanism by which science and technology may contribute to sustainable drylands development, combating desertification, reversing soil degradation in drylands, and to the identification of preventive measures to conserve natural resources [15].

Pursuant to increased threats of extreme climatic events worldwide, the United Nations Development Programme Drylands Development Centre (UNDP DDC) launched the Africa-Asia Drought Risk Management Peer Assistance Network (AADP). The network is financially supported by the Government of Japan. This network aims to mitigate the risks of drought and improve human livelihoods in Africa and Asia by creating an enabling environment for interregional knowledge sharing among drought-prone countries and facilitating exchange of knowledge in the two regions. In addition, in order to facilitate links between knowledge producers and users beyond regional boundaries, the AADP established an interregional network (African Drought Risk and Development Network [ADDN]) for drought management. The network works closely with UNDP and has created an opportunity for development and knowledge sharing between experts.

The domestic network or forum not only provides an opportunity for the vertical exchange of knowledge but also encourages local communities and local private sectors to participate and collaborate. In this regard, ADDN arranges annual African Drought Adaptation Forums (ADAF) and organizes a regular online discussion forum. The forums not only try to facilitate study tours and exchange visits, but also publish drought-related knowledge products, monthly newsletters, and policy briefs [55].

Therefore, it can be said that network activities as a public awareness tool strive to bring together expertise, experience, and perspectives from research institutes in developing and developed countries that are active in the area of climate change and drought. It provides a forum for rigorous research on the issues within the international climate change regime and means for further dialogue between countries working to address climate change, drought, desertification, and water management.

27.2.4 Linking Drought with Climate Changes in School

In our world, less than 3% of the water is available as freshwater, and more than 99% of freshwater available for direct human uses is groundwater. Climate and geology determines the characteristics, distribution, and availability of freshwater. Regional and global climate changes in the past are recorded in the rocks that show the variations and disruptions in the biogeochemical cycles that eventually led to mass extinctions. Groundwater may now be found in arid areas due to local geology and past climatic history. This water resource can only be used in a sustainable way if the spatial extension of the aquifer, temporal demand, and availability regimes are well understood. Climate has also consequences in agriculture and food security, frequencies of storms and rain, stability of coastal areas, biodiversity, and biological resources. Earth sciences and climate sciences are, thus, fundamental for modeling the most vital resource for life on earth. For the development of comprehensive models that define scenarios and forecasts for water management and policies, both at a national and intergovernmental level, the compulsory education system must be prepared to raise the profile of scientific literacy.

Human activity is responsible for climate changes, such as acid rain, stratospheric ozone depletion, and global warming. However, discussions of global climate change tend to focus on increasing surface temperatures. The accumulation of pollutants in the atmosphere also has consequences for public health. The natural greenhouse effect is caused primarily by water vapor: The irradiative balance at the earth's surface is modified by snow and ice cover; the distribution of vegetation types is sensitive to the local water balance; and regional climate patterns are influenced by ocean currents. The consequences of global warming due to human activities are change of rain patterns, glacier melting, increasing storm intensity, and rising sea level. Consequences of drought include the reduction of drinkable water and energy supplies, an increase in the number of forest fires, the reduction of biodiversity, a decrease in crop productivity, and desertification. Consequences of desertification include soil degradation, erosion, and groundwater contamination. Groundwater contamination is responsible for diseases and for spreading toxic chemicals. In this perspective, where earth systems are dynamic and connected to each other with profound impacts on human activities and societies, the education for climate change must be transversal not only to natural science disciplines but must also be included in the curricula of social sciences.

There are two basic strategies for dealing with the effects of global warming: climate-change mitigation, and adaptation to the changing conditions. Global warming affects evapotranspiration—the movement of water into the atmosphere from land and water surfaces and plants due to evaporation and transpiration—which is expected to lead to the expansion of dry areas and increased drought in dry areas [14].

The justifications for acting against climate change impacts vary across a range of moral and cognitive issues, economic interests, and political objectives. These differences affect the decision-making process at the national as well as international levels. In order to achieve positive and efficient implementation of strategies and measures, the importance of reducing communication disruptions between stakeholders has been stressed by many authors [2]. The responsibilities associated with the consequences and risks of climate change demand polycentric models of decision-making, as opposed to the traditional technocratic model, as well as the integration of forums of public debate [2]. The decision-making process has a bottom-up approach, determining at national-level policies according to governmental procedures and laws and coming together to generate an international consensus. An international framework for education on climate change, drought, and desertification is still lacking that can prepare the younger generations with a comprehensive view of local case studies, challenges, and demands for international debate in order to reform and create national laws and policies that can better respond to the socioeconomic impacts of climate changes and natural risks.

Orion [42] stated that one of the advantages in learning earth sciences is the development of environmental consciousness. Earth sciences provide students/citizens with the knowledge and capability to draw conclusions about different subjects, including energy and water management and saving, and the adequate use of natural resources. Besides, they can raise awareness for the environment in a student's region and the planet as a whole, and find the best tools to evaluate the changes that are happening in the environment. In the first international conference on education in earth sciences, which was hosted in England in 1993, the proposal to reinforce the environmental approach in earth sciences teaching was unanimously supported by the participants [34].

The balance between water demand and availability has reached a critical level in many areas of Europe. The reduced river flows, lowered lake and groundwater levels, and the drying up of wetlands are widely reported [21]. More than 50% of the water bodies in Europe are in poor ecological condition due to pollutants resulting from agriculture. The European summer of 2003 was characterized by highly anomalous meteorological conditions and was extremely hot and dry. More than half of the risk of 2003-like extreme European summers was attributable to human influences on the climate system [51]. They caused crop losses of US$12.3 billion, while forest fires in Portugal were responsible for an additional US$1.6 billion in damage. An unusual number of heat-related deaths were estimated between 22,000 and 35,000 across Europe as a whole.

An international cooperation research was undertaken between 2010 and 2013 in several countries from the European Union, namely Greece, Italy, Spain, Portugal, and Austria, in order to understand the present state of earth sciences teaching and learning in those countries. The target of the project was to define a framework of geosciences literacy principles for the general European citizens, to be applied, at least, for the revision of compulsory school curricula for secondary schools for the participant countries [25]. The curriculum comparison research of the earth sciences contents in secondary and high school shows a strong heterogeneity between those EU countries. Drought, water scarcity, and climate change can be found under the main subject "Human activities alter Earth," which has a good representation of 11% in Greece and 10% in Portugal, when compared with the whole frame of earth sciences subjects, but in Austria it is just 3%, Italy 2%, and Spain is not clearly represented [7]. In Portugal, the subjects find comprehensive analysis in natural sciences classes from the 8th grade and geography classes from the 9th grade (13–14-year-old pupils). Under GEOschools, an earth sciences interest analysis was conducted with 1749 14–17-year-old pupils and 58 teachers from urban, suburban, and countryside schools, in comparable proportions from Greece, Portugal, Italy, and Spain [26]. The results of the survey of the 190-question polls show that the students' interest in subjects such as Earth Protection and Sustainable Development are low, and Human Activities alter Earth is moderate, when compared with subjects like Natural Hazards or Paleontology.

Hands-on experience with the process of science creates connections. A new breed in formal education is needed, focusing on demonstrations of scientific principles and manipulative models. Schools through their practices and educational programs, and engagement of children in action to reduce emissions, and to reduce water consumption, can enhance children's learning and build their understanding of how they can respond to climate change and drought. Schools can set an example to today's children and young people who will be the vanguard of tomorrow's green economy [30]. In this regard, schools organize some educational programs such as establishing school summers for climate change and drought awareness. It is noteworthy that transferring environmental educational knowledge to children is difficult and requires tools and strategies. Boeckel [6] noted that art-based environmental education could be a strategy for natural crisis management and sustainability. Art is a tool for knowledge transfer especially for kids and schoolchildren. According to Osmo Rauhala [46], Art as a tool for facilitating knowledge transfer is one of man's antennae stretched out to sense the world. Art makes humans susceptible to new information, which may not necessarily come to us in the form of language. Organizing painting festivals on drought and climate change, and organizing rain dances in schools are good examples for integrating art and drought in primary schools and kindergartens.

The evidence shows that educational interventions are most successful when they focus on local, tangible, and actionable aspects of sustainable development, climate change, and environmental education, especially those that can be addressed by individual behavior.

In 2005, the UN declared the Decade for Water as a way to encourage transversal debate on water under the Objectives of the Millennium for the Development. The following year, the UNO declared the Year of the Deserts and Desertification to reinforce the debate. The year 2013 was declared the Year of Cooperation for Water. Water management requires international cooperation and agreement, also because it is the most important natural resource. The glaciers from the Tibetan plateau are the source of the most important rivers in Asia, providing water to two billion people, and irrigation for half of the rice crops in China and the most important agricultural regions of India and Pakistan. But these glaciers are shrinking fast and half of them may disappear by 2050. This forecast will have also major consequences for the electrical supply of these countries from Central Asia. The escalade of international tensions eventually will come to appear when countries that are poorer, but rich in glaciers, may restrict the water flow to their oil-rich neighbors. On the other hand, intensification of monsoons by the retreating glaciers will result in more violent storms, intense erosion of soils, increase in the frequency of landslides in mountainous regions, and more devastating floods in lowlands such as Bangladesh and Myanmar.

The fourth largest water reservoir in Africa, Lake Chad basin, covers areas from Chad, Cameroon, Niger, and Nigeria. Being very shallow, this lake is highly sensitive to drought periods and has shrunk from 26,000 km^2 to only 1,350 km^2 since 1960, due to overgrazing and increase of the pressure on the freshwater resources for agriculture and drinking [12]. In Libya, Megafezzan Lake was the size of England some two hundred thousand years ago. The Garama civilization flourished based on oasis agriculture [49]. They built a complex underground water channel system to irrigate the crops, avoiding loss by evaporation. Around 1000 km of channels can still be detected. Five thousand years ago rain was interrupted, lakes disappeared, and the desert returned to the Ubari area. Groundwater was reduced to levels that led to the collapse of the civilization 1500 years ago [49]. Recently, the Libyan government built the "Great Man-Made River." It is a network of pipes that supplies water to the Sahara Desert in Libya from the Nubian sandstone fossil aquifer system, which spans just over 2 million km^2, including also northwestern Sudan, northeastern Chad, southeastern Libya, and most of Egypt. It is the world's largest irrigation project. It consists of more than 1300 wells, most more than 500 m deep, and supplies 6,500,000 m^3 of freshwater per day to the cities of Tripoli, Benghazi, Sirte, and elsewhere, removing an estimated 2.37 km^3 per year for irrigation of the Kufra oasis [1]. In both Central Asian and North African scenarios, in different hydrogeological and climate settings, a scarcity of water compared to demand is resulting in conflicting international interests.

Through its Climate Change Education for Sustainable Development program, UNESCO aims to make climate change education a more central and visible part of the international response to climate change [56]. The program aims to help people understand the impact of global warming today and increase "climate literacy" among young people. This can be achieved by

- Strengthening the capacity of Member States to provide more comprehensive climate change education for sustainable development at compulsory school levels through improved education policy, analysis, research and planning, education and training of education planners, and training on curriculum review/reform

- Encouraging and enhancing innovative teaching approaches to integrate climate change education for sustainable development in schools through interdisciplinary practices, science education, whole school approaches, technical and vocational education and training, and education on disaster-risk reduction
- Raising awareness about climate change, and enhancing nonformal education through media, arts networking, and partnerships

International exchange and cooperation projects among schools shall be fostered and improved, particularly between schools from very different geographic contexts and water-management-related cultural backgrounds, with the support of intergovernmental organizations and NGOs.

UNICEF works on scaling up and mainstreaming climate change adaptation and disaster-risk reduction plans into the education sector. This work is based on the principles of child-friendly education and aims to integrate climate change, disaster risk, and environmental issues across the education system, including within policies and legislation, education sector plans and budgets, curricula and examinations, teacher education, school infrastructure and facilities, learning environments, and school governance and management. On any given day, more than a billion children are enrolled in primary or secondary school. But far too many of those enrolled children do not complete their education. Instead, they drop out because the quality of the education they receive is poor or because of challenges that make it difficult for them to attend and participate in school. These challenges include deepening poverty, gender imbalances, emergencies and conflict situations, HIV and AIDS, and disabilities. Chronic environmental degradation and climate-related hazards are also reasons why children cannot finish their education. While no area is immune to the impacts of climate change, evidence suggests that developing countries, which already struggle with social, economic, and environmental issues, will be worst hit by changes in rainfall patterns, greater weather extremes, and an increase in droughts and floods. In the near future, as a result of education applied to local challenges, more sustainable harvesting methods may be implemented, by improving soil productivity and reducing the risk of erosion, together with a better management of water resources based on more efficient irrigation systems. More time and better education may foster the development of business, generating income.

International cooperation may result in the development of national projects that raise the profile of drought and water scarcity in the frame of a dynamic changing climate within the education system. The AdaPT program was developed to support financially the work on "Adaptation to Climate Change" in Portugal. Its development was supervised according to the terms set out in the Memorandum of Understanding between Portugal, Norway, Iceland and Liechtenstein under the European Economic Area Financial Mechanism (EEA-Grants). The program was informed by the needs and contributions of the coordination group, the National Strategy for Adaptation to Climate Change. The proposed project areas of the program will contribute greatly to the expected results of the program: to increase capacity in order to assess vulnerability to climate change and to increase awareness and education on climate change. One of the proposed project areas is the "Education and Climate Change Award," which aims to integrate and complement environmental education concerning climate change, in a mitigation and adaptation approach to pilot school projects. One the project components will be a prize (funding) for the best project to implement measures related to climate change in schools.

Improving the educational system with the latest research data and a diversity of educational tools available is becoming easier by using web platforms for the subjects of drought, water scarcity, and climate change. These are becoming more common, more comprehensive, and more appealing to both teachers and pupils. These online resources enable a more balanced and international approach to education, introducing innovative tools and ideas that can be adapted to any cultural and economic environment. Diversity of educational resources in the classroom in any case introduces more pleasure to discovery and more focus on the resolution of problems [59]. For example, The NASA Innovations in Climate Education project includes a portfolio of 71 climate education initiatives that span across the United States, and contribute to the development of a climate-literate public [38]. The Climate Literacy and Energy Awareness

Network project, a part of the National Science Digital Library, provides a reviewed collection of resources to enhance students' understanding of the core ideas in climate and energy science, coupled with the tools to enable an online community to share and discuss teaching about climate and energy science [10]. The Environment Institute of Australia and New Zealand has been running and has just completed a 3-year program of Climate Skills training. It was funded by the Australian Government Department of Climate Change and Energy Efficiency and in partnership with Climate Change, Coasts, and Catchments at the University of the Sunshine Coast. Resources introduce practitioners to planned adaptation and mitigation responses to projected impacts of climate change. They also offer a doorway into the rapidly evolving fields of knowledge that are emerging as we seek to reduce vulnerability to climate change and adapt our systems to cope with its challenges [22]. The UK Environmental Change Network aims to support learning about our changing environment. It provides online resources for teaching, talks, open days, and hands-on activities for school students and adults, and an undergraduate placement, based with the ECN Moor House-Upper Teesdale ECN staff at Lancaster [20]. In Spain, several educational tools are proposed by different governmental and public organizations. *Know and Value Climate Change: Working Group Proposals* is a collective book and a source of activities to set climate change on a human scale. It was conceived for secondary school as well as universities and the general adult public [8]. *The Didactic Guidebook on Environmental Education and Climate Change* was developed for teachers and environmental educators on training courses [13]. *Climatosfera 2100* is an innovative didactic videogame and guidebook to work on the impacts of the climate change in the classroom (http://www.fundacion-ipade.org/climatosfera/).

In conclusion, the development of an international strategy that may effectively implement drought and water scarcity in the obligatory curricular system must not forget its ultimate consequence, desertification, which should be recognized as a direct effect of natural and/or human-related climate changes. The introduction of drought and climate changes in the compulsory school curricula must be transversal to both natural and social sciences and arts, providing a more comprehensive knowledge, based on regional realities, for public debate and development of more consensual policies for mitigation and adaptation. Professional development and training for teachers and education planners must be provided with the latest research results, involving the existing resources such as research centers and universities, science centers, and museums. International exchange and cooperation projects among schools shall be fostered and improved, particularly between schools from very different geographic contexts and water management-related cultural backgrounds, with the support of intergovernmental organizations and NGOs. Outdoor learning and mitigation or adaptation of local case studies must be implemented in school curricula together with the need to diversify educational resources on water management, such as the use of ICTs, like videogames or apps. Finally, in the information society an approximation of both teachers and pupils is expected to the most advanced technologies and researches that may expose the latest scientific discoveries in open seminars and workshops, creating a continuum of information and innovation within research-teaching-learning-decision-making.

27.3 Summary and Conclusions

Drought and climate change are natural disasters that can be induced by unsustainable human activities. Whereas lifestyle patterns are related to agriculture, forestry, and ranching in rural areas, with countryside tourism becoming more important in more recent years, drought has a huge negative impact on these areas. Hence, educational activities, public awareness, and public participation play a valuable role in drought management in rural as well as urban areas. Since students and young children are the future generation of the earth, linking climate change and drought with schools starting from kindergarten can be a good strategy for combating desertification and drought through awareness. In addition, museums can not only provide an understanding of drought for the public, but can also present a valuable sense of connection between before and after drought lifestyle patterns and landscapes, showing from research that the past and the present are the key to the future. On the other hand, networks create opportunities for knowledge sharing in sciences related to drought, earth, climate, and hydrology. Natural and human causes for climate change and global warming, drought and desertification, as well as the development of urgent mitigation policies, can only be effectively developed if schools, teachers and students, and the obligatory school curricula include those subjects as top priority under an international education framework developed in a short-term period. It can be concluded that educational activities, public awareness, and training tools allow individuals as members of society to explore drought issues, be engaged in problem solving, take action to improve the environment or reduce impacts, follow and respond to environmental challenges, and manage their behavior within the ecosystem in order to live in a more sustainable way.

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28

Policy Framework of Drought Risk Mitigation

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Abstract Drought represents a potentially disastrous threat to water supplies, agriculture, and environment. The severity of its impacts makes the traditional emergency approach inadequate and calls for a risk management approach, particularly in order to reduce water shortages in water supply systems. In this chapter the role of legal and institutional frameworks is discussed, with particular reference to the actions aimed at reducing vulnerability to drought, as natural hazard, suggested by the International Strategy for Disaster Reduction (ISDR) and by the European Union. Contents of drought-planning instruments (at strategic, tactical, and emergency levels) to define preparedness and mitigation measures are discussed. The methods for the assessment of water shortage due to drought in water supply systems are described with reference to the strategic planning and to the operation of systems. The review focuses on: (1) the drought indices to be used for an effective monitoring and early warning system, (2) the methods to assess the risk of water shortage due to drought, and (3) the measures for reducing societal vulnerability to drought and mitigating its impacts. Better coordination among the drought-preparedness planning tasks and the adaptive operation of water supply systems to prevent severe shortages also through a more extensive use of early drought warning are suggested. Further research needs are identified.

28.1 Introduction

Long and severe droughts have the potential to alter radically the way of life of the people affected and to produce a lot of damages in water supplies, agriculture and environment, with heavy consequences on economy, health, and social well-being. Occurrences of droughts increase conflicts among the competitive users of water in arid and semiarid countries. Furthermore, the quality of water worsens during the most severe drought episodes. In the experience of the last decades, drought is in first place on the list of disasters in terms of affected population and of damages [69]. Whereas droughts occurring in developed countries primarily result in economic losses, prolonged droughts in developing countries, especially in Africa, contribute to malnutrition, famine, loss of life, and migration [66]. Drought risk is expected to increase in the future, due to climatic changes that could lead to precipitation reduction and temperature increase in several regions [31]. Furthermore, other global changes, such as population growth, urban sprawl, population shift from humid to more arid regions, massive tourism in coastal areas, and pollution, will likely increase vulnerability of many regions to drought, leading to conditions of permanent water scarcity. So, the necessity of an effective drought management has been recognized not only by water managers but also by policy makers at different levels. This is a very positive step for improving political and institutional frameworks, which represent a key factor of a successful strategy for drought risk reduction.

It is interesting to note that some initiatives to support policies and governance aimed at drought preparedness and mitigation have been developed at international level (e.g., within the UN Strategy for disaster reduction [66]) and at European level (e.g., through the efforts of the European Commission to address drought and water scarcity issues into the water policy established by Water Framework Directive [18–20]). Also, specific criteria and guidelines have been suggested for coping with drought in Mediterranean European countries [41].

According to the results of two recent public opinion surveys in the United States [63], it seems that the public is willing to support the government response to drought, requiring a robust and new policy framework to identify drought risk and impacts and to implement effective measures.

This chapter describes, in the first part, the evolution of the approaches to drought management and discusses the role of legal and institutional frameworks with particular reference to the actions suggested to reduce the vulnerability to drought, as natural hazard, by the ISDR and by the European Union. Then, planning instruments to define the drought preparedness and mitigation measures are presented. The methods for the assessment of water shortage in water supply systems are described with reference to the strategic planning and to the real-time operation of systems. Particular attention is paid to the choice of drought indices for early warning system, able to mitigate the drought impacts.

28.2 Legal and Institutional Frameworks for Drought Management

28.2.1 Response to Drought: From Crisis Management to Risk Management Approach

A severe drought can be considered a natural disaster, and, similarly to other disasters, its impacts on society depend on the vulnerability of affected sectors and the preparedness to implement appropriate mitigation measures [43]. However, drought management presents some peculiarities with respects to other disasters: (1) a prevention action may be effectively planned since drought effects evolve slowly along a large time span; (2) the strategic measures for improving drought preparedness are generally more complex, since the spectrum of potential long-term actions is very large; and (3) the operational measures, to be implemented once a drought begins, require an adaptive response to the dynamic character of drought by taking into account the uncertainty in the drought evolution, namely a duration and a severity different than the ones considered in the planning stage.

Broadly speaking, the nature of the response to drought events can be distinguished into two main categories [52]. The *reactive approach,* or *emergency management*, consists of measures conceived and implemented once a drought occurs and its impacts are perceived. It includes the measures taken during and after the drought event to minimize the drought impact. Often it is termed as a *crisis management* approach because it is not based on specific plans prepared in advance.

Conversely, the *proactive approach* or *risk management* consists of measures conceived and prepared according to a planning strategy rather than within an emergency framework. Such measures are devised and implemented before, during, and after the drought event on the basis of a comprehensive drought management plan.

Since the risk management approach seems to have become a new successful paradigm, it is opportune, as preliminary stage, to clarify the meaning of the term "risk" within this strategy, as different definitions of "risk" have been adopted in the past and in various disciplines. In particular, the two main categories of risk include the following: (1) risk as the probability of an adverse event or (2) risk as the expected consequence of an adverse event. The first category includes the concepts of risk adopted in the statistical hydrology and in reliability theory. According to the statistical hydrology, risk is defined as the probability that a hydrological variable X (e.g., maximum annual discharge) exceeds a given threshold x_0 at least once in n years, which, assuming stationarity and independence of the events, can be computed by the known formula:

$$\text{Risk} = 1 - P\left(X \le x_0\right)^n \tag{28.1}$$

According to reliability theory, risk is defined as the probability of failure for the system under investigation, that is, as the probability that the load L (the external forcing factor) exceeds the resistance R (an intrinsic characteristic of the system), leading to a failure (Mays and Tung [39]):

$$\text{Risk} = P\left(L \ge R\right) \tag{28.2}$$

The definition of the second category, developed within the strategies for natural disasters mitigation, considers risk as "the expected loss due to a particular natural phenomenon," to be evaluated as function of natural hazard, exposure to the natural hazard, and vulnerability to the event. The natural hazard is taken into account through the probability of occurrence of a potentially damaging phenomenon, whereas the vulnerability describes the degree of loss for a given element at risk. According to this definition, risk can be measured in economic terms (damages) or social terms (e.g., lost lives).

The fight against drought has been traditionally carried out according to a *crisis management* approach. Although this approach still represents the most common response to drought, there is an increasing awareness of its weaknesses since it implies last-minute decisions that generally lead to expensive actions, with unsustainable environmental and social impacts.

A shift toward a *risk management* approach with measures planned in advance has been progressively advocated [51,68,74]. Today, such a shift is emphasized in policy instruments adopted in the more drought-prone countries such as Australia [4], South Africa, and the United States [70]. It is also suggested by almost all the findings of recent research programs on drought, as analyzed by XEROCHORE's final documents [71]. Unfortunately, it is less evident in local, national, and international policy agenda on drought issues as well as in the legislation and institutional framework of water resources management.

28.2.2 Law and Institutions for Coping with Drought

The core of the risk management approach consists in the development of appropriate planning tools, including assessment of drought risk, development of a drought early warning system, and definition of preparedness and mitigation measures aimed at preventing or reducing economic losses and social and environmental impacts.

Several countries, affected by the repeated occurrence of severe droughts, have developed national drought policies in recent decades. In many cases, the planning legislation to cope with drought refers to principles and criteria developed either by the UN Convention for Combating Desertification [67] or from the UN International Strategy for Disaster Reduction [65,66]. Also some laws refer to the Integrated Water Resources Management (IWRM) [25] paradigm, introduced in the UN Conference on Water in the Mar del Plata (1977), and emphasized at subsequent several international water events, such as World Water Forums [26]. Other laws deal with the drought threat within the actions assigned to the Civil Protection services in the field of natural disasters.

In general terms, these drought policies are strongly affected by the national legal framework and by the structure of the institutions that shared the governance of water. For example, Spain, as a country which has suffered the heavy impacts of very severe drought events, has established an advanced legislation aimed at reducing the risk of water shortage, due to drought, in water supply systems. In particular, according to the National Hydrological Plan Act (2001), Drought Management Plans have been adopted by the River Basin Authorities for all districts and a national drought indicator system has been developed. Such a system is able to describe the basin drought status (i.e., normal, pre-alert, alert, and emergency) through a set of variables in order to implement adequate actions to mitigate impacts [21]. This legislation, founded on a remarkable role of the River Basin Authorities, has been the main driver of the European policy for drought, which suggest to prepare a specific drought management plan according to the guidelines issued on 2007 [18]. Also, particularly interesting is the comparison of the drought policies carried out in Australia, South Africa, and United States [70]. The analysis, concerning the evolution of the drought planning processes in these countries, despite the differences among each national approach, shows that the same goal of reducing societal vulnerability to drought pushes to adopt innovative approaches and to emphasize very similar features of risk management, including monitoring and early warning, risk assessment, and a mixture of preparedness measures.

28.2.3 Actions for Drought Risk Reduction within the International Strategy for Disaster Reduction

The risk management approach, as discussed earlier, is the basic methodology adopted in the international strategy for disaster reduction. In particular, the general procedure, established at *the World Conference on Disaster Reduction* (Kobe, Hyogo, Japan, 2005), within the "Hyogo Framework for Action 2005–2015," has identified the following priorities to build resilience of nations and communities to drought [66]: (1) policy and governance, (2) drought risk identification and early warning, (3) awareness and education, (4) reducing underlying factors of drought risk, and (5) mitigation and preparedness, as well as cross-cutting issues.

In particular, a set of principles that should guide the development of national and local strategies for reducing drought risk has been identified as follows [66]:

- Political commitment, high-level engagement, strong institutional setting, clear responsibilities both at central and local levels, and appropriate governance are essential for integrating drought risk issues into a sustainable development and disaster risk reduction process.
- A bottom-up approach with effective decentralization and active community participation for drought risk management in planning, decision making, and implementation is essential to move from policy to practice.
- Capacity building and knowledge development are usually required to help build political commitment, competent institutions, and an informed constituency.
- Drought risk reduction policies should establish a clear set of principles or operating guidelines to govern the management of drought and its impacts, including the development of a preparedness plan that lays out a strategy to achieve these objectives.
- Drought-related policies and plans should emphasize risk reduction (prevention, mitigation, and preparedness) rather than relying solely on drought (often turned into famine) relief.

- Drought monitoring, risk assessment, and other appropriate risk reduction measures are principal components of drought policies and plans.
- Institutional mechanisms (policy, legislative and organizational) should be developed and enforced to ensure that drought risk reduction strategies are carried out.
- Sound development of long-term investment in risk reduction measures (prevention, mitigation, and preparedness) is essential to reduce the effects of drought.

28.2.4 Recommendations for Drought Management in the European Union

In past decades, European water policies did not deserve particular attention to drought issues in terms of technical and financial instruments and legislative acts. The Water Framework Directive 2000/60 (WFD)—which promoted a complex water resources planning process at basin level aimed at preserving or improving water quality in order to safeguard human uses and ecosystems protection—dealt marginally with drought. Although drought mitigation is mentioned among the Directive objectives and drought events are considered exceptional circumstances that enable for a derogation of requirements of good ecological status of water bodies. In order to overcome these weaknesses in EU water policy, the EU Water Scarcity and Drought Expert Network has developed a guidance document on drought preparedness and mitigation [18] with the proposal of drafting a "Drought Management Plan" (DMP), as an annex to the "River Basin Management Plan" (RBMP). Such a DMP should be prepared by the same body responsible for basin planning, that is, the River basin (or district) Authority. In spite of the fact that the DMP is not mandatory for Member States, it aims at extending goals and criteria of WFD (in a similar way to the EU Flood Directive 2007/60) to improve drought management and in particular to reduce the vulnerability of the water supply systems and to mitigate drought impact. Its specific objectives are: (1) to guarantee sufficient water availability to cover essential human needs to ensure the population's health and life, (2) to avoid or minimize negative drought impact on water bodies, (3) to minimize negative effects on economic activities [53].

On the basis of the successive work of the EU Water Scarcity and Drought Expert Network, recently, the report from the commission to the European Parliament and the Council on these issues [20] has suggested revising of the related European policy, including some specific topics listed in Table 28.1 [54].

At the EU level, discussions are ongoing on how Member States should incorporate climate change considerations into the implementation of EU water policy, in order to minimize vulnerability to future climate change and to fight possible emergencies by preparing specific response actions. According to the White Paper on *Adapting to climate change* [12], one of the strategies proposed to increase resilience

TABLE 28.1 Recommendations to Revise European Policy on Water Scarcity and Drought

Improving water efficiency
• Introducing water saving devices and practices in buildings and improving water-efficient construction
• Reducing water leakages in supply distribution systems
• Improving efficiency in agricultural use of water
Achieving better planning and preparedness to deal with droughts
• Integrating actions against water scarcity and drought into other sectorial policies (agriculture, households, industry)
• Assessing the adequacy of the River Basin Management Plans on water scarcity and drought issues
• Further developing the prototype of an observatory and early warning system on drought
• Defining a more comprehensive list of indicators on water scarcity, drought and of vulnerability of water resources
Developing adequate implementation instruments of financing, water pricing, water allocation research, and education
• Encouraging EU funding of natural risks through Cohesion Policy, Regional Policy, Solidarity Fund, and Economic Recovery Plan, and reforming Common Agricultural Policy
• Making the national rules more restrictive to authorize water abstractions
• Developing new research projects on vulnerability and increased drought risk
• Introducing new educational programs and awareness-raising campaigns

to climate change consists in the improvement of the management of water resources. With specific reference to water scarcity, such a water management should promote further measures to enhance water efficiency in agriculture, households, and buildings. Also, the expected revision of the WFD and of the water scarcity and droughts strategy include options to increase drought resilience. Furthermore, revisions of the River Basin Management Plans (due in 2015 and 2021) are indicated as the concrete occasion to incorporate climate changes within basin planning, through analysis of the pressures on the water bodies, definition of the phenomena to be monitored, and verification of the resilience of the action program to climate change.

As part of the actions included in the White Paper, the Guidance Document no. 24 under the Common Implementation Strategy for the WFD [19] examined the ways to ensure that the River Basin Management Plans are climate-proof. This document suggests both actions to monitor and detect climate change effects in the water resources and to develop adaptation measures to water scarcity and drought. In particular, the following principles have been emphasized: (1) to handle available scientific knowledge and uncertainties about climate change; (2) to develop strategies that build adaptive capacity for managing climate risks; (3) to integrate adaptive management within key steps of the RBMP of the WFD; and (4) to address the specific challenges of managing future flood risk and water scarcity and drought. The same Document, in order to revise the traditional concept of water resources planning, suggests some actions concerning institutional, water supply management, and interdisciplinary aspects:

- To strengthen the institutions in charge of water management to prepare them for the challenges that lie ahead
- To build robustness into water resources systems by integrating multiple sources of supply and water demands in conjunctive systems and by improving and enlarging the water transportation and distribution infrastructure to achieve the best possible allocation of available resources
- To discuss adaptation measures related to water scarcity and droughts in a trans-boundary and interdisciplinary contexts

As a follow-up step to this, the 2012 EU Water revision ("Blueprint to Safeguard European Waters"), also on the basis of the analysis of the RBMP issued for European districts, will assess achievements and will identify further requirements toward long-term sustainable water use across the EU. For this process, a better-harmonized approach on drought risk management at all levels of governance (EU, national, regional, river basin) is proposed in order to integrate drought management policy into water resources management [35].

28.3 Planning Instruments for Drought Risk Management

28.3.1 Planning Levels for Reducing Drought Risk

The drought phenomenon presents different features and impacts for each element of the natural hydrological cycle and/or of the water resource system (Figure 28.1). In particular, the severity of drought impact on a water supply system and, consequently, on the socioeconomic sectors is mainly connected to the vulnerability of the different involved elements. The risk of water shortage in water supply systems differs from natural drought risk because the water shortage results from an imbalance between water supply and demand, which is caused by a meteorological/hydrological phenomenon, but is affected by other time-varying factors such as demand pattern development, supply infrastructures, and management strategies, and especially by the type of measures adopted for coping with drought. In consequence, the more complex phase of the drought risk management is the one related to the prevention and mitigation of water shortage in water supply systems.

In general terms, risk-based drought management requires the following main steps: planning, monitoring, implementation of planned measures, management of emergency situations, and recovery from damages.

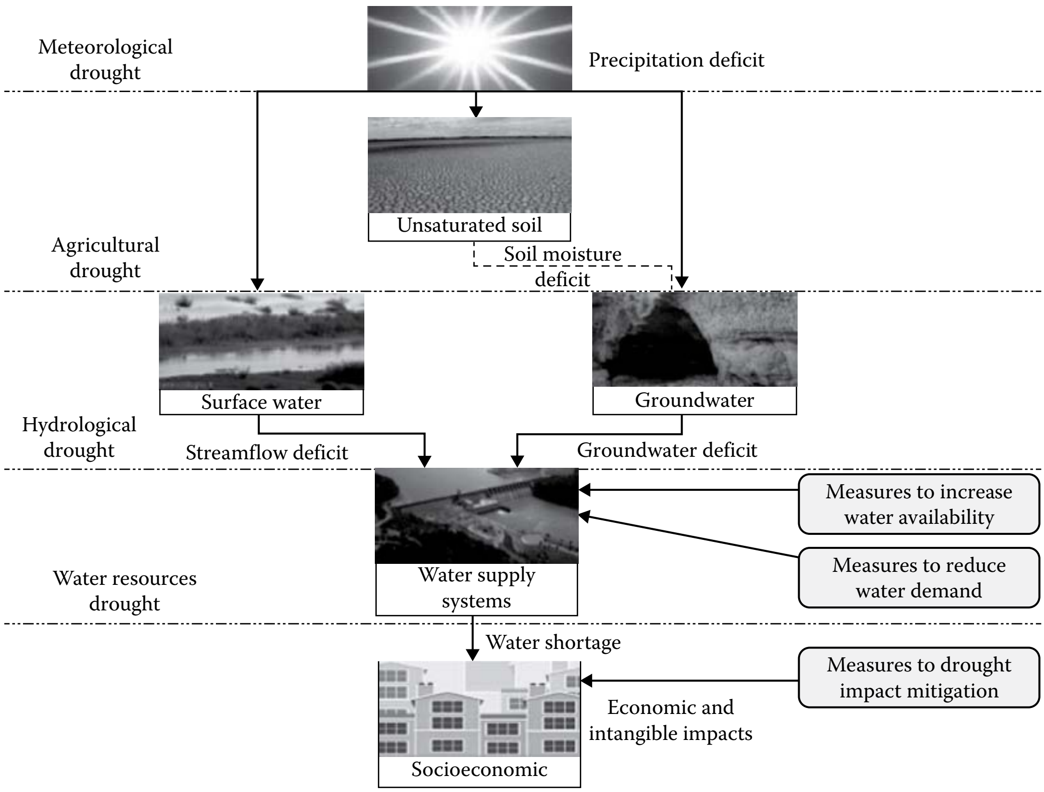

FIGURE 28.1 Drought phenomenon and role of drought management measures.

Different levels of drought planning may be necessary according to the legislative and institutional framework of each country and, particularly, to the sharing of the competences among the different institutions involved. At least three levels have to be distinguished to face general drought risk and shortage risk in water supply [58]: (1) the general planning of the measures to cope with drought risk at basin level, (2) the planning of preventive actions within the water supply system operation, and (3) the planning of emergency measures during a drought event that is recognized as a natural disaster.

The three different plans are the Strategic Drought Preparedness Plan (SDPP), the Water Supply System Operation under Drought Conditions Plan (WSSOP), and the Drought Contingency Plan (DCP).

The general objective of the Strategic Plan is to reduce the susceptibility to drought impact of the river basin, and particularly to reduce the risk of water shortages due to drought. The SDPP should be prepared by the same bodies responsible for water resources planning, that is, River Basin or District Authorities according to the EU Water Framework Directive. It can be considered a "Drought Management (sub) Plan" to be attached to the River Basin Management Plan according to the indications given by the Water Scarcity and Drought Expert Network.

The Water Supply System Operation Plan should include measures to be adopted by the organizations that manage water supply systems to prevent the onset of a real water emergency.

The Drought Contingency Plan should include, among other items, short-term measures to be adopted when exceptional droughts cause considerable damage and a natural disaster is declared.

The main contents of the three plans are reported in Table 28.2.

The first plan, at strategic level, aims at identifying the drought vulnerable areas within the river basin—through the analysis of past drought events and their impacts—and to estimate the water shortage risk in water systems as preliminary stages for defining, comparing, and selecting long-term measures, including

TABLE 28.2 Main Contents of Drought Management Plans

Plan	Responsible Body	Contents

Strategic Drought Preparedness Plan (SDSPP)	River Basin Authority	• Identification of drought-vulnerable areas, through the analysis of past drought events and their impacts
		• Estimation of water shortage risk in water supply systems taking into account
		  • Definition of the priority in water allocation under shortage conditions among different uses
		  • Definition of guarantee levels for different uses (expressed as time reliability and volumetric reliability)
		  • Definition of appropriate long-term actions to reduce water shortage risk
		• Comparison and selection of alternative drought mitigation measures
		• Procedures to ensure the transparency of information on drought situation and planning process and to allow public participation in the decisions
		• General indications for the drafting of Water Supply System Management Plan (WSSOP)
		• Estimation of costs and financing sources
		• General indications for the drafting of Drought Contingency Plan (DCP)

Water Supply System Operation Plan (WSSOP)	Agencies for Water Supply Management	• Definition of indicators and their values to define Normal, Alert, and Alarm conditions with respect to drought for a given water supply system • Definition of the best mix of long-term and short-term measures to avoid emergency • Estimation of costs and financing sources for the chosen mitigation measures • Tools for fostering the stakeholder participation and exchanges
Drought Contingency Plan (DCP)	Regions or Basin Authorities (with the contribution of Civil Protection)	• Definition of indicators and their values for declaration of a drought as natural calamity • Tools for an institutional participation through a devoted task force on drought • Definition of short-term mitigation measures and their costs • Indications for the coordination of state, regional, and local interventions during emergency • Tools to ensure the transparency of information on drought situation • Possible recovery from drought damages

Source: Rossi, G. et al., Strategic water shortage preparedness plan for complex water supply systems, in Tsakiris, G. (ed.), *Proceedings of International Symposium "Water Shortage Management,"* CANAH-NTUA, Athens, Greece, 2008, pp. 65–81.

procedures for information transparency and public participation. The same plan has to give general indications for drafting the other two plans.

The second plan (WSSOP) aims at defining the best combination of long-term and short-term measures within each water supply system designed to prevent drought emergency.

Finally, the Contingency Plan represents the planning tool, which includes the drought indicator level for calamity declaration, defines short-term measures to be adopted to mitigate its impacts and to recover relative damage.

The proposed planning framework for drought risk management in water supply systems is reported in Figure 28.2, which shows the role of the main preliminary investigations and of the drought monitoring system into the process of development and implementation of the Plans.

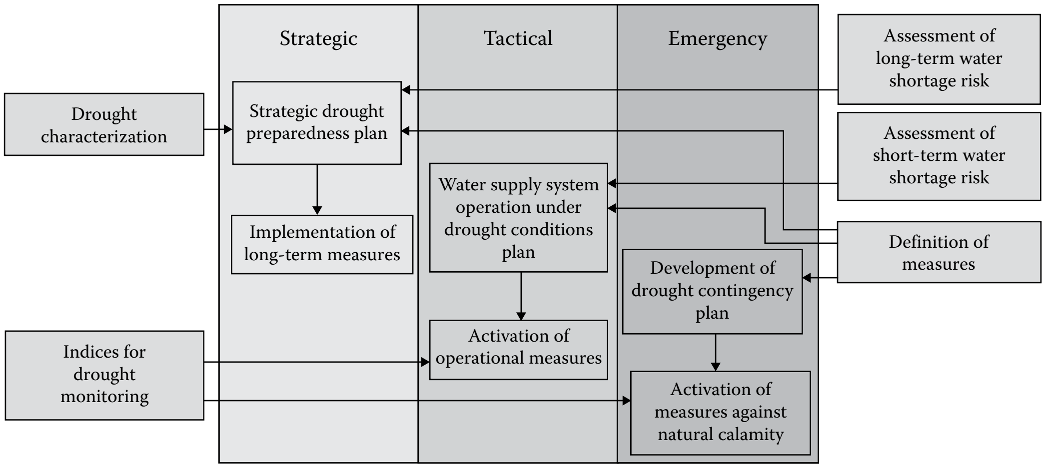

FIGURE 28.2 Role of preliminary investigations and early warning system in the development and implementation of drought management plans. (From Rossi, G. et al., *Options Méditerrannées, Serie A*, 80, 251, 2008.)

28.3.2 Role of Drought Monitoring Systems

The identification and quantification of a drought and consequently the assessment of the drought vulnerability of an affected area and/or of the water supply systems can be carried out through a set of different methodologies. An objective procedure that serves to identify the start and the end of drought, evaluating its characteristics (duration and magnitude) and assessing the probability of the event, consists in the application of "run method" on the time series of the variable of interest [72]. The "run method" has been applied for probabilistic characterization of drought through univariate, bivariate, and spatial–temporal analyses (among recent reviews, see Bonaccorso et al. [2]; Cancelliere and Salas [5], Mishra and Singh [44]).

The development of a drought monitoring system generally requires the selection of appropriate indices that describe drought conditions through the measure of the anomaly from a "normal" situation for one or more meteorological or hydrological variables. The several proposed indices for drought monitoring mainly differ according to the selected variable, the time scale, the definition of "normal" condition, the way of measuring the anomaly (e.g., difference, ratio), and the method for standardization.

Several reviews and classifications of drought indices have been made in last decades. Among the most recent, examples can be found in MEDROPLAN [41]; Niemeyer [48] and on Internet websites such as National Drought Information Center [46].

Generally, drought indices are categorized in meteorological, hydrological, agricultural, remote-sensing-based drought indices. Some indices also attempt to combine different data related to different variables (e.g., precipitation, soil, water content) and/or to merge the information from several indices into one value taking into account also the status of water reserves.

Since an effective response to drought depends on the early perception through reliable monitoring, the indices to be used in a drought monitoring system have to satisfy several requisites such as [57]

1. Representing the complex interrelation between meteorological and hydrological components of a significant reduction of water availability
2. Making use of real-time easy available hydro-meteorological data
3. Being able to describe drought conditions even in a drought's early stages
4. Providing comparability of drought events both in time and space

TABLE 28.3 Comparison among Some of the Most Used Drought Indices

Index	Strength	Weakness	Spatial Comparability	Relevance for Impact Assessment	Suitability for Monitoring
PHDI—Palmer Hydrological Drought Index [49]	• Detailed estimate of hydrological drought based on soil moisture balance	• Classes of drought severity not consistent in terms of probability of occurrence	• Poor since empirical parameters estimated for arid regions of USA	• Good description of agricultural impacts	• Large use in monitoring systems (although it underestimates drought in wet regions)
SPI—Standardized Precipitation Index [40]	• Simple computation and easy interpretation • Drought categories based on probability	• Severity of drought events sensitive to aggregation time scale	• Very high for fixed time scale • Difficulties to compare events of different duration	• Good description of severity of generic impacts	• Very large use for early warning of drought
RDI—Reconnaissance Drought Index [64]	• Estimate based on precipitation and potential evapotranspiration PET • Able to analyze climatic change	• Necessity of data for computing PET • Drought description very similar to SPI being variability of PET lower than precipitation	• Very high for fixed time scale	• Good description of agricultural impacts	• Use yet limited
DFI—Drought Frequency Index [24]	• Asymptotic estimation of return period considering persistent deviation from normal • Slightly sensitive to the selected threshold	• Complex computation under the hypothesis of randomness and time independence of considered variable	• Very high since index is slightly sensitive to threshold, time scale and characteristics (i.e., duration, cumulative deficit)	• Depending on the selected variable • Poor relevance since drought characteristics not directly representative of impacts	• Difficult application since index is oriented to probabilistic characterization of drought

Source: Rossi, G. et al., *Options Méditerrannées, Serie A*, 80, 251, 2008.

5. Describing in some way drought impact
6. Assessing the severity of the current drought as a trigger to support decision makers to activate drought mitigation actions

Table 28.3 summarizes a comparison among the most consolidated indices (Palmer, SPI) and a few new indices (as RDI and DFI) aimed at exploring strengths and weaknesses, spatial comparability, relevance as proxy of critical impact, and suitability for a monitoring system.

An early drought warning system has to be developed, by connecting to a station networks of meteorological and hydrological data, including remote sensing data, and by using an advanced DSS, running on adequate computer facilities in terms of computational power and user-friendly interface.

The main objective of a drought warning system is to allow the most appropriate drought prevention and mitigation measure to be implemented, through reliable triggering mechanisms tested in advance through simulation of the considered system.

28.3.3 Measures for Drought Preparedness and Mitigation

In literature, several classifications of drought mitigation measures are available. A consolidated classification of drought mitigation measures distinguishes three main categories oriented to: (1) increase water supply, (2) reduce water demands, and (3) minimize drought impacts [73,74]. Other traditional classifications are based on the typology of approach to the drought phenomenon, either reactive or proactive or in relation to the timing of their implementation, differentiating between *long-term* measures aimed at improving drought preparedness and which includes a set of structural and nonstructural adjustments to an existing water supply system, and *short-term* measures, defined within a contingency plan, designed to mitigate drought events when they have already started, through actions oriented to improve water supply through new sources or to reduce water demand [17].

In Tables 28.4, a list of long-term and short-term mitigation measures is reported, with reference to the main categories of actions mentioned earlier and to different sectors of application (urban, agricultural, industrial, and recreational).

More recently, the EU Water Scarcity and Drought Expert Network [18] proposed several drought measures distinguishing (1) preventing/strategic measures to be applied during normal status, (2) operative (tactic or emergency) measures including actions on demands, on supply, and on environment, (3) operative measures to be activated during pre-alert, alert, and emergency conditions, (4) Drought management Plan follow-up measures, and (5) recovery measures with the deactivation of supply actions and restrictions.

A different classification of measures, set up for the mitigation of general natural hazards, drought included, has been recently proposed within the CONHAZ project [15]. It distinguishes the following categories: (1) risk management planning and adaptation plans; (2) hazard modification; (3) infrastructures; (4) mitigation measures *stricto sensu*; (5) communication; (6) monitoring and early warning; (7) emergency response; (8) financial incentives; and (9) risk transfer.

Regardless of the adopted classification, after a set of potential mitigation measures are identified, selection of the best combination should be based on a comparison and ranking of the performance of each measure in mitigating any negative impact of drought as well as of the main economic, environmental, and social consequences of the adopted measure. To this end, multi-criteria approaches have been proposed since the pioneer work by Duckstein [16], who described the multiple viewpoints to be adopted in a multi-criteria approach and has discussed the set of available specific multi-criteria methods such as ELECTRE and compromise programming. The NAIADE model has been applied to different complex water systems, in order to rank the alternative combinations of long-term and short-term measures for reducing shortage risk in a water supply system [45,55].

TABLE 28.4 Long-Term and Short-Term Drought Mitigation Measures

Category	Long-Term Actions	Affected Sectors			
Demand reduction	Economic incentives for water saving	U	A	I	R
	Agronomic techniques for reducing water consumption		A		
	Dry crops instead of irrigated crops		A		
	Dual distribution network for urban use	U			
	Water recycling in industries			I	
Water supply increase	Conveyance networks for bidirectional exchanges	U	A	I	
	Reuse of treated wastewater		A	I	R
	Inter-basin and within-basin water transfers	U	A	I	R
	Construction of new reservoirs or increase of storage volume of existing reservoirs	U	A	I	
	Construction of farm ponds		A		
	Desalination of brackish or saline waters	U	A		R
	Control of seepage and evaporation losses	U	A	I	
Impacts minimization	Education activities for improving drought preparedness and/or permanent water saving	U	A	I	
	Reallocation of water resources based on water quality requirements	U	A	I	R
	Development of early warning systems	U	A	I	R
	Implementation of a Drought Contingency Plan	U	A	I	R
	Insurance programs		A	I	
Category	**Short-Term Actions**	**Affected Sectors**			
Demand reduction	Public information campaign for water saving	U	A	I	R
	Restriction in some urban water uses (i.e., car washing, gardening, etc.)	U			
	Restriction of irrigation of annual crops		A		
	Pricing	U	A	I	R
	Mandatory rationing	U	A	I	R
Water supply increase	Improvement of existing water systems efficiency (leak detection programs, new operating rules, etc.)	U	A	I	
	Use of additional sources of low quality or high exploitation cost	U	A	I	R
	Over exploitation of aquifers or use of groundwater reserves	U	A	I	
	Increased diversion by relaxing ecological or recreational use constraints	U	A	I	R
Impacts minimization	Temporary reallocation of water resources	U	A	I	R
	Public aids to compensate income losses	U	A	I	
	Tax reduction or delay of payment deadline	U	A	I	
	Public aids for crops insurance		A		

Source: Rossi, G., Drought mitigation measures: A comprehensive framework, in Vogt, J.V. and Somma, F. (eds.), *Drought and Drought Mitigation in Europe*, Kluwer, Dordrecht, the Netherlands, 2000, pp. 233–246.
U, Urban; A, agricultural; I, industrial; R, recreational.

28.4 Drought Risk Mitigation in Water Supply Systems

28.4.1 Water Shortage Assessment in the Strategic Planning

Assessment of water shortage risk due to drought is a key step within strategic planning of drought preparedness measures in water supply systems [14]. In addition, risk assessment can also find useful application during the operation of a water supply system in order to select among different management alternatives. When dealing with strategic decisions, risk assessment generally needs to be unconditional, for example, not referred to a particular state or condition of the system and be aimed at selecting the best long-term measures [3]. In the case of the operation of water supply systems under drought conditions, the risk assessment has to be "conditional," that is, taking into account the initial state/condition of the system. In this case, the main problem is deciding *when* and *how* to activate adequate mitigation measures (i.e., rationing policies and/or use of additional water resources) in order to prevent future severe shortages [10]. Due to the uncertainty of future drought development, the decision should be taken on the basis of an assessment of shortage risk due to drought while also introducing the drought measures in the system model. These predefined measures in many cases are implemented in different stages, according to an interactive approach and have to be established according to the different conditions of the water system (e.g., normal, alert, alarm) [41].

The economic assessment of drought damage and of preparedness and mitigation measures has been the subject of a great deal of literature. A review of the different methodologies proposed has been carried out in two recent EC-funded projects, namely XEROCHORE [71] and CONHAZ [15]. However, due to the lack of appropriate data, combined with the relative complexity of the economical assessment of damages, the analysis of a water supply system management under drought conditions has been traditionally carried out assuming water shortage as proxy of damages. Thus, drought risk has been assessed in terms of the probabilistic features of water shortages due to droughts, with reference to the different demands.

In general terms, the impact of droughts on water supply greatly depends on the characteristics of water storage facilities, their operating rules, the temporal distribution of water demands, as well as on the actions taken to reduce drought impact. It follows that a correct approach to risk assessment should take into account both the Hazard (i.e., drought occurrences) as well as the vulnerability of the water supply system, which depends on the physical characteristics of the system, as well as on the demands and on management factors. To this end, a Monte Carlo simulation of the system, where the probabilistic features of droughts are implicitly taken into account making use of stochastic models to generate hydrological inputs and where the vulnerability of the system is considered in the simulation stage, may constitute an efficient tool to assess water shortage risk (Figure 28.3).

As previously mentioned, assessment of water shortage risk due to droughts can be carried out with reference to two distinct objectives, namely that of increasing the robustness of the system within the

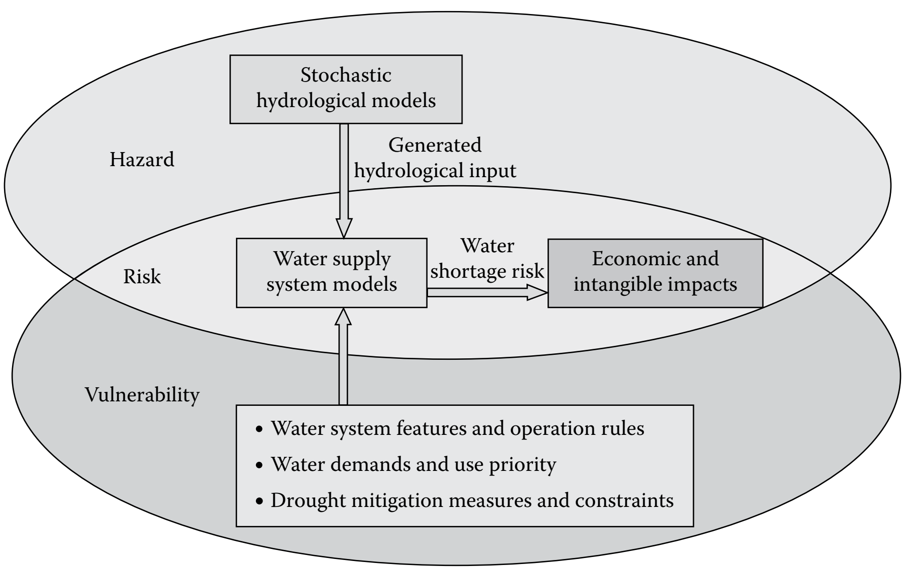

FIGURE 28.3 Assessment of water shortage risk due to drought in a water supply system through Monte Carlo simulation.

planning stage, including the definition of appropriate mitigation strategies, as well as improving the performance of water supply during droughts within the operation stage.

Several procedures have been proposed to assess the long-term adequacy of a water supply system to satisfy demands during drought events since the study of Russel et al. [60], which proposed to estimate the expected losses due to drought as a function of the "level of adjustment" of the water system, defined basically as a demand–supply ratio. The evaluation of the performance of a water resources system generally has been made through appropriate criteria or indices, attempting to quantify shortage amounts and occurrences through the concepts of reliability, resiliency, and vulnerability [27]. More recently, the use of probabilities of shortage of different levels of severity also to evaluate the different drought mitigation measures is becoming a popular procedure [1,56].

Some studies make use of the concept of "design drought" like the one by Frick et al. [22], which assessed the capability of a water system to cope with drought by simulating its performance during a fixed-return-period drought derived from long hydrological generated series, taking into account the planned expansion of the system. Cancelliere et al. [6] studied the relationship between the severity of droughts identified through the "run method" and performance indices for a reservoir with different demand patterns by using the standard operating policy (SOP) and a few hedging policies, showing that the shortage characteristics cannot be computed on the basis of a single design drought and that the use of a Monte Carlo analysis should be preferred in order to evaluate shortage risk.

Johnson and Kohne [33] explored the possibility of using the Palmer hydrological drought index for a preliminary assessment of the susceptibility of reservoirs to drought aimed at a more detailed investigation for those more vulnerable.

When the focus of the planning of complex water supply systems under drought risk is on the evaluation of drought mitigation measures, the decision making includes: (1) the sharing of water shortages among different users, (2) the temporal distribution of release from each source, (3) the priority of release from various sources. In this case, a Decision Support System (DSS), with the purpose of helping decision makers facilitate the use of models and databases, and a multi-criteria technique that allows for a comparison and ranking of measure alternatives to face drought and reduce shortage can be appropriate.

Many studies have been proposed to help water system managers in the planning of the drought mitigation measures through expert systems and DSS. Among the recent examples, a knowledge-based system to evaluate different drought management options has been developed by Karavitis [36] while Merabtene et al. [42] developed a DSS to assess the susceptibility of water supply system to drought and to determine optimal release through the minimization of drought risk by using a genetic algorithm for a system in Japan. A DSS based on optimization and neuro-fuzzy technique has been proposed by Cancelliere et al. [9].

28.4.2 Water Shortage Assessment during the Operation of Water Supply Systems

A greater number of papers have been devoted to evaluating the risk of water shortage with the aim of defining operating policy or storage allocation in a single reservoir and/or complex water supply system in response to drought.

In particular, the definition of operating rules, following the approach proposed by Young [75] has been carried out through optimization procedures for computing the optimal set of releases on the basis of a given objective function [37] and by expressing the relationship between optimal release and hydrological inputs and system-state variables by means of different techniques, including, but not limited to, linear regressions, piecewise regressions, neural networks, and neuro-fuzzy systems. Among the several papers applying this approach for the operation under drought conditions it may be worthwhile to mention: Randall et al. [50]; Jain et al. [32]; Chandramouli and Raman [13]; Cancelliere et al. [7,8].

Other papers have focused on the operation of water systems under drought conditions by using other tools. Hirsh [28] estimated the risk of reservoir storage falling below a certain level over a specified time horizon by using several generated streamflow series and computing the selected storage based on the current state of the reservoir and withdrawal rate. Jowitt et al. [34] presented a computer-based DSS for group of reservoirs developed in order to modify the current reservoir control curve in response to drought events. In particular, a simulation model was applied, able to calculate the cumulative monthly sequences of natural inflows and/or pumped supplies from groundwater or river abstractions. Shih and Revelle [61] derived demand-management policy rules during droughts or impending droughts for a single reservoir. The signal used for calling rationing is a trigger volume given in terms of months of demand (as a volume) that are needed in storage. When the sum of actual storage plus anticipated inflow is less than the trigger volume, rationing is initiated.

Shih and Revelle [62] presented a mixed integer programming model that determines, in a water supply reservoir, the triggers that activate several phases of rationing under the objective of maximizing months without rationing, given a limit on the number of months with a second phase rationing. Lund [38] developed storage allocation rules among reservoirs, which are part of a system operated under drought conditions in order to reduce evaporative and seepage losses, thus demonstrating that balancing storage among reservoirs, a common practice where each reservoir is filled to a similar percentage of its overall capacity, does not minimize water losses during droughts.

28.4.3 Early Warning and Reduction of Drought Impacts

Some studies focus on integrating early warning system information within drought management of water supply systems. Huang and Yuan [29] developed a color-coded early warning system for drought management on the real-time multi-reservoir operation. Garrote et al. [23] presented a procedure to link operational drought indicators (including precipitation, streamflow, reservoir storage, and/or groundwater piezometric levels) to drought management policy in the Tagus supply system in Spain. The drought management policy consisted of a large set of actions, including demand restrictions and emergency works. Huang and Chou [30] introduced a risk-based decision process integrated into a drought early warning system for reservoir operation. Cañón et al. [11] used the Drought Frequency Index (DFI) as a drought indicator triggering mechanism for multi-reservoir system operations during drought through a multilevel, nonlinear optimization procedure designed to reduce water deficits in irrigation districts.

Nicolosi et al. [47] used a heuristic multi-objective approach based on genetic algorithms and Monte Carlo simulation in order to define triggering levels to activate mitigation measures, and which thereby verify the performance of the procedure using an observed and generated series.

Rossi et al. [59] proposed a methodology for managing water supply systems during droughts based on the assessment of conditional risk of future shortages and on the consequent activation of mitigation measures. More specifically, the methodology is based on the computation of an indicator of shortage probability caused by drought through Monte Carlo simulation of the behavior of the water supply system within a short-term horizon starting from its current condition making use of several stochastically generated streamflow series.

28.5 Summary and Conclusions

This chapter has discussed the key elements of legal and institutional framework of drought management, emphasizing the role of a set of planning instruments able to (1) assess the risk of water shortage due to drought, (2) identify the measures to prevent and mitigate economic and social impact, and (3) define the indicators in an early drought warning system and related triggers to implement the mitigation measures. On the basis of review of several methods and applications cases, the following conclusions can be drawn.

First, in general terms, an effective drought management in water supply systems requires an integrated approach that includes the same list of elements proposed by Grigg, to improve water resources management, namely policy sectors, water sectors, government units, organizational levels, functions of management, geographic units, phases of management, disciplines, and professions. However, drought management can be considered a more difficult challenge due to several specific weaknesses and gaps, which affect the planning, organization, and implementation of drought preparedness and mitigation actions.

A conceptual misinterpretation still exists between *water scarcity* (i.e., a permanent unbalance between available water resources and demands) and *drought* (i.e., a natural temporary negative deviation from normal precipitation amount for a significant duration and extension, which leads to a temporary water shortage in a supply system). In order to overcome this weakness, a specific plan aimed at drought preparedness and mitigation has to be adopted within the general planning regarding water resources uses and water quality protection.

In addition, the need of a complex institutional structure for coping with drought risk is not fully recognized. Indeed, the river basin authority cannot, in many countries, cover all specific tasks of effective drought mitigation and recovery. Therefore, it appears necessary to entrust the bodies responsible for each water supply system to define in advance the measures to face water shortage risk, in particular for basic needs such as for municipal use, according to common national criteria. Furthermore, general criteria for declaring drought as a natural disaster should be developed at the national level, while emergency management organizations should intervene at local level within a predefined emergency plan.

Also the very important role of an advanced early drought warning, including appropriate drought indicators and triggering thresholds for a timely implementation of the measures, has to be highlighted.

Second, despite the interesting outcomes of several research projects on drought, which recently have fostered a renewed interest toward this hazard, a list of future researches, aimed at improving resilience to drought of water systems and society, should include the following topics:

- Better modeling of drought occurrence and characteristics, both in terms of their stochastic nature and links with global atmospheric circulation patterns; especially the analysis should take into account climatic changes
- Thorough analysis of the past experiences in drought monitoring and mitigation as well as a greater knowledge-exchange on the measures adopted in different geographic and societal contexts, in order to implement best practices in drought management
- Advanced assessment of economic, environmental, and societal impacts of droughts and of drought mitigation measures, preferably based on multi-criteria tools
- Development of appropriate models and integrated packages of techniques, which can be easily understood and applied by decision makers in order to use, within the drought preparedness planning, the more advanced results in specific drought-related topics (e.g., stochastic hydrology for drought characterization; economics and environmental sciences for a comprehensive impact evaluation; social sciences for selecting the way to reduce users conflicts)
- Development of advanced tools for an "adaptive" drought management in water supply systems, based on an early drought warning system, including reliable monitoring and forecasting system and advanced DSS, by using the improved computer facilities available within water utilities and regulators

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29

Drought Law and Policy

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Abstract Drought is a natural phenomenon in which human demand for water exceeds the natural availability of water extensively. It is, therefore, not as purely a physical phenomenon that can be defined by weather. Drought affects all components of the water cycle, ranging from a deficit in soil moisture through reduced groundwater recharge and levels, and low stream flow or dried-up rivers. Drought has wide-ranging social, environmental, and economic impact, with consequences on agriculture and health. Drought can be natural and brought about by the ever-changing climate or can be man-made due to poor management of soil, water, and air pollution. Since drought is a global phenomenon, the necessity for a global approach in tackling its menace is imminent. This has led to enactment of policies and laws at international levels to be domesticated at national levels. The institutional framework for drought-related law and policies entails the activities of such organizations as United Nations Environment Programme (UNEP), World Meteorology Organization (WMO), Food and Agriculture Organization (FAO), International Panel on Climate Change (IPCC), African Union (AU), United Nations Economic Compassion for Europe (UNECE), International Law Commission (ILC), and many others. Policies on drought are dynamic and are subject to periodic modifications as occasioned by different outcomes. Drought-related laws can generally be classified as primary or secondary. The primary drought laws are directed toward drought declaration, notification, and management, while secondary laws are directed toward prevention of man-made contributing factors and management. At national levels, different organizations and departments are responsible for enactment of drought policies and as such may be at local, state, or national government levels. However, the underpinnings of successful implementation of these policies include public participation, access to information, and enforcement.

29.1 Introduction

Drought can be defined as a natural phenomenon in which human demand for water exceeds the natural availability of water extensively. Drought is a global problem and its impact can be far-reaching, resulting in food insecurity, malnutrition, mass death, economic and material losses, migration, displacement, health challenges and so on. Drought is also classified as a disaster if in an enormous scale; demand for water may lead to conflicts and wars between sovereign states. Therefore, water laws are also applicable to drought because drought can occur naturally or can be brought about by human activities and it is important that policies are put into place to prevent their occurrence and to manage the events effectively if they occur unavoidably.

Public policies are those that are developed by governmental bodies and officials. Non-governmental actors and factors of course may also influence policy development. However, the special characteristics of public policies stem from the fact that they are formulated by what David Easton has called the "authorities" in political system, namely, elders, paramount chiefs, executives, legislators, judges, administrators, councilors, monarchs, and the like. These are the people who engage in the daily affairs of a political system and are recognized by most members of the system as having responsibility for these matters and take actions that are accepted as binding most of the time by most of the members so long as they act within the limits of their roles [8]. Law is the art of interpretation and application of rules and obligations in a broad sense; it can be further described as a body of rules and principles of human conduct within a community, which by common concept of that community is established by local custom or conduct, decreed by legislative authority, or derived by court decisions that shall be enforced by an external power. Like several environmental-related laws, drought laws rely heavily on scientific evidence. It is such evidence that can cause a local government, state, or nation to declare a drought event. Drought laws shape drought policy for a community. Many laws on drought are emerging and are derived from various international conventions on environment. Law as it relates to drought is dynamic and periodic review is occasioned by different outcomes of drought events, and adaptation to such events. Several environmental laws as well as drought laws are also emerging at various levels of governance.

There are many institutions responsible for drought law and policy at international, national, state, and local government levels. However, enforcement is more pronounced at the local government level than at any other level. At the international level, organizations that are relevant in shaping drought policy include UNEP, FAO, WMO, UNDP, UNC, and IPCC. At the state (national) level, environmental protection agencies (EPAs), Department and Ministries of Agriculture, Disaster Management Agencies, Drought and Desertification Agencies, and National Meteorological Agencies are quite relevant in policy-making and implementation. The nexus between policy and law is quite compelling. The laws are the underpinnings of the policies and also the basis for enforcement. Therefore, successful drought prevention and management depends on the level of enforcement of drought policy [12]. Like all environmental laws, drought law depends greatly on scientific evidence. It is therefore essential to discuss the factors contributing to drought since these laws are enacted with reference to the contributing factors.

29.1.1 Contributory Factors of Drought

Many factors contribute to drought, as stated inter alia, and these can be natural or man-made. It is, however, important to prevent drought as far as is humanly possible. Some of the contributing factors to drought include soil degradation, deforestation, air pollution, depletion of the ozone layer, global warming, climate change, and forest fires. Droughts can persist for several years and a short, intense drought can cause significant damage to the local economy, while prolonged droughts can cause mass migration and humanitarian crises. Periods to droughts can have significant environmental, agricultural, health, economic, and social consequences. Furthermore, the effects in vulnerability vary; for example, subsistence farmers are more likely to migrate during drought because they do not have alternative food sources. This brings about inequality in impact and response of drought. The combination of climate change and deforestation increase the drying effect of dead trees, which fuels forest fires. Generally, shortage of precipitation is the major cause of drought. Rainfall is related to the amount of water vapor carried by regional atmosphere, combined with the upward forcing of the air mass containing that water vapor. If these combined factors do not support precipitation volumes sufficient to reach the surface, the result is drought.

Human activities can directly trigger the exacerbating factors: over-farming, excessive irrigation, deforestation, and erosion adversely impact the ability of the land to capture and hold water. Furthermore, global climate change can trigger droughts with substantial impact on agriculture throughout the world, with greater impact in developing countries. Overall, global warming will cause increased rainfall, with subsequent flooding and erosion in some regions but droughts in some others. Therefore, drought laws and policies are designed based on causes, impact, and mitigation efforts.

29.1.2 Environmental Governance

Governance involves what happens when many people live together and depend on each other. It is about negotiation and achievement of common goals such as peace, prosperity, and happiness. It deals with community, states, markets and interaction of politics, economies, land management, sociology, and international relations. The interaction between environmentalists and commercial interests is mediated by a complex of culture, history, technology, economics, and law. This complexity needs to be bridged to create a dialogue between those who focus on international commerce and those concerned with the ethical grounds for managing the global environment. Humans require clean air, freshwater, and adequate food for continued survival. It is against this backdrop that environmental policies are enacted. There is need for reconciliation of different social aspects with regard to sustainable use of environmental resources as a basis for sustainable development at any scale from local to global and in any context worldwide [7].

Environmental law provides the foundation for governance approaches and management policies directed toward environmental conservation and the sustainable usage of natural resources. Much of the modern body of environmental law has been developed internationally through the adoption of international conventions; but numerous agreements have also been concluded at the regional level or on a bilateral basis. All legal instruments need to be implemented at the national level through appropriate national legislation in order to ensure adequate application and compliance. Unfortunately, a multitude of states within the international system either lack the specific environmental legislation or the human resources needed for the implementation of Multilateral Environment Agreements (MEA).

29.1.2.1 Environmental Rights

"Human rights" is the quest for an order of human dignity and has become the guiding light for law and policy. Not only are governments bound by them but increasingly businesses and private sector are called or mandated to observe these rights as well. Environmental rights is the interface between right to healthy environment with human rights such as life, health, personal integrity, food, housing, information, public participation, natural resources, livelihood, and remedies. One of the key issues in developing countries is food insecurity, which prevents access to essential nutrition, commonly resulting from poverty, recurrent drought, civil wars, soil and land degradation.

29.2 International Environmental Law and Drought

Environmental law is an essential tool for the governance and management of sustainable development. It provides the foundation for governmental policies and actions for the conservation of the environment and for ensuring that the use of natural resources is both equitable and sustainable. Law and policy are responding to increasing environmental deterioration produced by natural causes such as volcanic eruptions and by human intervention. However, law cannot affect the natural processes that cause environmental changes but can and does regulate human behavior, including such that prevent or respond to natural disasters.

29.2.1 Concepts and Historical Perspectives

The definition of environment affects the scope of legal rules, which are intended to protect the environment. A series of legal texts, both national and international recognized at underpin the end of the 1960s the urgent necessity to protect the environment. Some of the earlier ones include deceleration of the council of the *European Economic Community* (*EEC*) *of 27 June 1967*, which defines environment as follows:

> Water, air and land and their relationships as well as relationships between them and any living organism.

Among international texts, which often provide the basis for national laws concerning environmental protection, is the *1972 UN Stockholm Declaration on the Human Environment* [14], which states that

> "the protection and improvement of the human environment is a major issue which affects the well being of peoples and economic development throughout the world. Man's capability to transform natural surroundings can bring to all peoples the opportunity to enhance the quality of life, it also can do incalculable harm to human beings and the environment when wrongly or heedlessly applied"

The aftermath of the Stockholm conference witnessed the establishment of UNEP and the Environment Fund, which was created to support its activities to actively sustain and coordinate the actions of other international institutions. In addition, there are some specialized UN organizations involved in the development and implementation of environmental law. Examples of these are Food and Agriculture Organization (FAO), World Meteorology Organization (WMO), United Nations Economic Commission for Europe (UNECE), among others.

- *The World Charter for Nature; United Nations General Assembly on 28 October 1982*, which was adopted, proclaimed that

  > "Mankind is a part of nature and life depends on the uninterrupted functioning of natural systems which ensure the supply of energy and nutrients. Every form of life is unique and merits respect regardless of its worth to man. Civilization is also rooted in nature, which has shaped human culture and influenced all artistic and scientific achievement. However, humans can alter nature and exhaust and therefore, they must fully recognize the urgency of maintaining the stability and quality of nature and of conserving natural resources. Lasting benefits from nature depend upon the maintenance of essential ecological processes and life support systems and upon the diversity of life forms, which are jeopardized through excessive exploitation and habitat destruction of man. The degradation of natural systems owing to excessive consumption and misuse of natural resources, as well as through failure to establish an appropriate economic, social and political framework of civilization. Competition for scarce resources creates conflicts whereas the conservation of nature and natural resources contributes to justice. As a consequence, man must acquire knowledge to maintain and enhance his ability to use natural resources in a manner, which ensures the preservation of species and ecosystems for the benefit, of present and future generation."*

- *1992 Rio de Janeiro Earth Summit Declaration on Environment and Development*
  The Declaration on Environment and Development was made at the 1992 Rio de Janeiro Earth Summit and was adopted on June 14, 1992, by the representatives of 172 states. All but six members of the United Nations have built upon such principle. One of the fundamentals of the declaration can be found in Principle 4, which states

  > "In order to achieve sustainable development, environmental protection shall constitute an integral part of the development process and cannot be considered in isolation from it"†

* The World Charter for Nature, United Nations General Assembly, October 28, 1982.

† 1992 Rio de Janeiro Earth Summit Declaration on Environment and Development.

- *2002 Johannesburg World Summit on Sustainable Development*
  At the summit convened in Johannesburg, more than 190 countries adopted a declaration affirming their will to

  > "assume a collective responsibility to advance and strengthen the independent and mutually reinforcing pillars of sustainable development—economic development, social development and environmental protection at local, national, regional and global levels"*

29.2.2 Role of Law in Environmental Protection

Law can be viewed as binding norms adopted by the public authorities through procedures accepted as valid for their creation. Such procedures allow law to be distinguished from moral principles and religious belief as well as etiquettes or rules of social conduct, the respect of which cannot be imposed by public authorities. The obligatory character of law and the sanctions, which can ensure the enforcement of legal rules, should prevent and eliminate acts and behaviors that are detrimental to the environment. However, nonbinding principles and rules formulated in recommendations or declarations by international organizations or conferences play an increasing role in international law, especially in the field of environmental protection. These function to guide state authorities and also other actors in their action and they can also contribute to the emergence of new obligatory rules. The concept of justice requires the need to take into account legitimate interests that otherwise would not be protected in environmental law; there are sometimes conflict of interests and there are also the needs to address them. Economic factors play an important role in internationalizing efforts to safeguard the environment.

29.2.3 Subjects of International Law

Conceptual international law only recognized states as actors in international relations. States have the exclusive right to conclude treaties, send and receive diplomatic representatives. Since the proliferation of international conventions protecting human rights, and the environment, individuals, and nongovernmental organizations are becoming participants as observers and in some instances key players in formulation of international laws. According to the present state of international law, individuals are entitled to have rights, which can be internationally enforced mostly in the framework of specific treaties guaranteeing their fundamental rights and freedoms and creating specific enforcement mechanisms [13].

Unlike classical international legal relations, wherein traditional rules apply, international environmental law has its variation in the sense that there are provisions for public participation, scientific evidence, and capacity building, which extend beyond state participation. Often, capacity building needs international cooperation and assistance, which are key elements in enhancing the role that the new actors are able to play. Particularly important in this regard is *Article 19 of the 1994 Convention to Combat Desertification in those countries experiencing serious Drought and or Desertification, Particularly in Africa.*† Another provision for public participation in international environmental law can be found in *Principle 10 of the Rio Declaration,* which recognizes individual right to information, participation, and remedies in environmental matters.

29.2.4 Institutional Framework

Unlike all other international relations, international environmental law has been developed and applied not only by and between nation-states but also through the activities of national social institutions other than states at the global or regional level for general or sectoral purposes. In addition, there is a wide range

* 2002 Johannesburg World Summit on Sustainable Development.
† United Nations Convention to Combat Desertification (UNCCD) 1994.

of international nongovernmental organizations (NGOs) whose input in initiating, developing, and enactment of international environmental laws cannot be overemphasized. For example, the International Union of Conservation of Nature (IUCN), whose statutes were adopted at Fontainebleau in 1948 by a Conference of States, governmental agencies, and NGOs is registered as an association under Article 60 of the Swiss Civil Code; and the World Wide Fund for Nature (WWF), whose 1994 revised statutes were adopted by representatives of national (nongovernmental) organizations in 28 countries, was set up as a foundation under Article 80 of the Swiss Civil Code. Another veritable example is the *Helsinki Rules* on the uses of the waters of international rivers adopted by the International Law [7] Association at its 1966 session, which is referred to as the foundational regulation for the development of international water law. Furthermore, representatives of transnational corporations (TNCs) such as International Air Transport Association (IATA) actively participate in the development and application of environmentally relevant policies and legal instruments.

The functions of international organizations with regards to environmental law may be normative (e.g., adoption of "hard law treaties," "soft law" guidelines, or "case law" dispute resolution), operational (e.g., administrative implementation of agreements, including financial and technical support), or communicative (e.g., reporting and dissemination of legal information). For the purpose of this chapter, only some of the major international organizations will be discussed. And these include United Nations Environment Programme (UNEP), World Meteorological Organization (WMO), Food and Agriculture Organization (FAO), United Nations Commission on Human Rights (UNCHR), International Civil Aviation Organization (ICAO), International Machine Organization (IMO), International Atomic Energy Agency (IACA), World Health Organization (WHO), International Labor Organization (ILO), World Trade Organization (WTO), World Bank Group (WBG), World Intellectual Property Organization (WIPO), and UN Educational Scientific and Cultural Organization (UNESCO) [1].

1. *United Nations Environment Programme* (*UNEP*)
   The United Nations Environment Programme (UNEP) is the leading global environmental authority that sets the global environmental agenda, promotes the coherent implementations of the environmental dimension of sustainable development within the United Nations System, and serves as an authoritative advocate for the global environment. UNEP was established sequel to the United Nations Conference on the Human Environment in 1972 and has its headquarters in Nairobi, Kenya, in addition six regional offices and various country offices. UNEP has aided in the formulation of guidelines and treaties on issues such as the international trade in potentially harmful chemical, trans-boundary air pollution, and contamination of international waterways.*
2. *World Meteorological Organization* (*WMO*)
   The World Meteorological Organization was established in 1951 as a specialized agency of the United Nations for weather, climate, operational hydrology, and related geophysical sciences. The Convention of the World Meteorological Organization was signed on October 11, 1947. It has its origin in the International Meteorological Organization (IMO) founded in 1873. WMO provides a framework for international cooperation in the development of meteorology and operational hydrology and their practical application. WMO plays a leading role in international efforts to monitor and protect the environment through its program. In collaboration with other UN agencies and the National Meteorological and Hydrological Services, WMO supports the implementation of a number of environmental conventions and is instrumental in providing advice and assessments to governments on related matters. The WMO and UNEP jointly created the Intergovernmental Panel on Climate Change (IPCC). It is also directly responsible for the creation of the Global Atmosphere Watch (GAW). For their efforts the IPCC received the 2007 Nobel Peace Prize. The WMO secretariat is based in Geneva, Switzerland.†

* UNEP, www.unep.org.
† WMO, www.wmo.org.

3. *Food and Agriculture Organization* (*FAO*)
   The FAO is an agency of the United Nations that leads international efforts to defeat hunger. One of the notable aims of FAO is to make agriculture, forestry, and fisheries more productive and sustainable by promoting evidence-based policies and practices to support highly productive agricultural sectors, while ensuring that the natural resource base does not suffer in the process. Some of the policies initiated by the FAO include (a) Right to food guidelines; (b) International Plant Protection Convention (IPPC), in 1952; (c) Integrated Pest Management; (d) Emergency Prevention System for Trans-boundary Animal and Plant Pests and Diseases, in 1994; (e) Global Partnership Initiative for Plant Breeding Capacity Building; and (f) FAO Soil Charter, among many others. The FAO is headquartered in Rome, Italy.*
4. *African Union* (*AU*)
   The African Union (AU) is a continental union consisting of 54 countries in Africa. The only African state that is not a member is Morocco. The AU was established on May 26, 2001, in Addis Ababa with the aim of replacing the Organization of African Unity (OAU). The AU, among many other roles, established the African Charter on Human and Peoples Rights and many environmental instruments.†
5. *Organization of American States* (*OAS*)
   The OAS was founded on May 5, 1948, with 21 founding members but is now an association of 35 independent states of the Americas with headquarters in Washington, DC. The OAS was established to promote sustainable development, peace security, free trade, and human rights. The organization established the Inter-American Convention Human Rights in 1979. The American Convention on Human Rights signed in 1969 came into force in 1978.‡
6. *United Nations Economic Commission for Europe* (*UNECE*)
   The UNECE was established in 1947 to encourage economic cooperation among its member states. It is one of the five regional commissions under the administrative direction of the United Nations headquarters. It is composed of 56 members, including European countries, Canada, Central Asian Republics, the United States, and Israel. UNECE reports to UN Economic and Social Council (ECOSOC). The concern for environment enabled the establishment of the Committee on Environmental Policy (CEP), which is the overall governing body of UNECE environmental activities. UNECE has many conventions to her credit and these include *Espoo Convention, Aarhus Convention, Convention on Long-Range Trans-boundary Air Pollution, Convention on the Protection and Use of Trans-boundary Water Courses and International Lakes, and Convention on the Trans-boundary Effects of Industrial Accidents*.§
7. *The United Nations Commission on Human Rights* (*UNCHR*)
   The UNCHR was established in 1946 by ECOSOC. It met for the first time in January 1947 and established a drafting committee for the Universal Declaration of Human Rights, which was adopted by the United Nations on December 10, 1948. The commission held its final meeting in Geneva on March 27, 2006, and was replaced by the United Nations Human Rights Council (UNHRC) in the same year. The Commission on Human Rights established 30 special procedures or mechanisms to address specific country situations or thematic issues such as freedom of expression and opinion, torture, the right to food, right to education, safe environment, and sanitation.¶

* FAO, www.fao.org.
† AU, www.au.org.
‡ OAS, www.oas.org.
§ UNECE, www.unece.org/env.
¶ See 1966 International Covenant on Civil and Political Rights (ICCPR).

TABLE 29.1 Environmental-Related Specialized Agencies Autonomous Agencies in the UN System

Organization	Composition	Environmental Law Functions
International Labor Organization (ILO), Geneva, Switzerland	171 member states	Global conventions/standards for working environment National capacity building, incl. labor legislation
Food and Agriculture Organization (FAO), Rome, Italy	174 member states	Global/regional conventions and codes of conduct on fisheries (starting with 1949 General Fisheries Council for the Mediterranean, GFCM), agriculture (e.g., 1951 International Plant Protection Convention, IPPC). Pesticides, genetic resources (under Commission on Genetic Resources for Food and Agriculture, CGRFA) National capacity building, incl. natural resource legislation
UN Educational, Scientific, and Cultural Organization (UNESCO), Paris, France	184 member states	Global conventions (e.g., 1972 World Heritage Convention, follow-up by World Heritage Centre WHC) and action programs (e.g., MAB biosphere reserves network, and marine science under Intergovernmental Oceanographic Commission, IOC)
International Civil Aviation Organization (ICAO), Montreal, Quebec, Canada	185 member states	Global treaty standards for aircraft emission/noise, transport of dangerous goods National capacity building, incl. aviation legislation
World Health Organization (WHO), Geneva, Switzerland	190 member states	Global/regional health and toxicity standards National capacity building, incl. health organization
World Meteorological Organization (WMO), Geneva, Switzerland	179 member states	Global monitoring of air pollution/climate change
International Maritime Organization (IMO), London, United Kingdom	155 member states	Global conventions and codes of conduct for marine pollution control (mainly Marine Environment Protection Committee, MEPC) and liability National capacity building, incl. maritime legislation
World Intellectual Property Organization (WIPO), Geneva, Switzerland	163 member states	Global conventions on intellectual and industrial property, incl. plant varieties, genetic resources (with International Union for the Protection of New Varieties of Plants, UPOV) National capacity building, incl. patent/trademark legislation
International Atomic Energy Agency (IAEA), Vienna, Austria	124 member states	Global conventions/standards on nuclear safety, liability and radiation protection National capacity building, incl. nuclear legislation
World Trade Organization (WTO), Geneva, Switzerland	130 member states	Global trade agreements (GATT), environmental aspects under Committee on Trade and Environment (CTE) Dispute settlement mechanism (DSB)
World Bank Group, Washington, DC		Operational policies for development projects, incl. environmental and natural resource management, follow-up by Independent Inspection Panel (IIP) National capacity building, incl. environmental legislation

8. *UN Office for International Strategy for the Reduction of Disaster Risks* (*ISDR*)
UNISDR was established in 1999 as a dedicated secretariat to facilitate the implementation of the International Strategy for Disaster Reduction (ISDR). It is mandated by the United Nations General Assembly Resolution (56/195) to serve as the focal point in the United Nations system for the coordination of disaster reduction and to ensure synergies among the disaster reduction activities of the United Nations system and regional organizations and activities in

socioeconomic and humanitarian fields. It is an organizational unit of the UN Secretariat and is led by the UN Special Representative of the Secretary-General for Disaster Risk Reduction (SRSG). UNISDR has five regional offices—in Asia (Bangkok), Africa (Nairobi), Europe (Brussels), Arab States (Cairo), and Americas and the Caribbean (Panama)—and the UNISDR Headquarters in Geneva. UNISDR also maintains a UN Headquarters liaison office in New York, a liaison office in Bonn, and field presence in Rio de Janeiro, Kobe, Suva, Incheon, and Almaty. UNISDR defines itself through its multi-stakeholder coordination approach based on the relationships it has developed with national and local governments, intergovernmental organizations, and civil society, including the private sector, and by its mode of operating through a network of global partners* (Table 29.1).

29.2.5 Implementation and Enforcement

Implementation and enforcement of international environmental law entails ensuring those who are governed by such rules comply with them. However, enforcement of international law differs from that of domestic law to the extent that the international community has no executive power, no police, and no obligatory jurisdiction. Nevertheless, there are different mechanisms to encourage compliance and these include negotiations, persuasion, pressure of public opinion, technical assistance, financial incentives, drafting of good texts and sanctions when necessary.

29.2.5.1 Strengthening Domestic Implementation Mechanism

In most instances, international environmental laws are not enforceable in states unless they are domesticated in the national laws. A major difficulty in implementing environmental treaties may arise from the inability of national legal systems to correctly apply rules formulated on the international level to be enshrined in the national law. Constitutional obstacles can make timely or full compliance with environmental treaty provisions more difficult. Another problem of concern is the lack of knowledge of international environmental rules and how to implement them by national executive bodies. Here again, capacity building and awareness building can help in resolving these problems. In this respect, assistance by international bodies or NGOs could be required. In addition, domestic remedies should be available to enforce international rules. Individuals and NGOs can be encouraged to bring complaints to courts or to the administrative authorities for lack of compliance with an international obligation of the state. This notion is enshrined in *Principle 10 of the 1992 Rio Declaration:*

> "each individual shall have appropriate access to information concerning the environment that is held by public authorities, including information on hazardous materials and activities in their communities and the opportunity to participate in decision-making processes. States shall facilitate and encourage public awareness and participation by making information widely available."
>
> "Effective access to judicial and administrative proceedings, including redress and remedy shall be provided"

This principle was also proclaimed by a considerable number of environmental treaties including the *1998 UNECE Aarhus Convention on Access to Information and Public Participation in Decision-Making and Access to Justice on Environmental Matters*, adopted in Aarhus, Denmark on June 23, 1998, under the authority of the United Nations Economic Commission for Europe and applicable only to member states of UNECE.†

* UNISDR, http://www.unisdr.

† UN Doc ECE/CEP/43, Adopted at the *Fourth UNECE Ministerial Conference*, Aarhus, Denmark, June 25, 1998.

29.2.6 "Hard" and "Soft" Law Instruments

International treaties and customary law are hard law instruments because of their obligatory characters. Texts adopted by international conferences and organizations are generally not binding on states if these bodies have not been given authority to adopt obligatory texts, and so the texts are referred to as "soft" law due to their nonobligatory status but are provided to guide state behavior. Examples of soft law and instruments include *European Soil Charter* of 1972,[*] Food and Agriculture Organization (FAO), *World Soil Charter 1981*,[†] *UNEP World Soils Policy 1982*,[‡] and *UNEPs' Strategy on Land Use Management and Soil Conversations of 2004*.[§] It, however, suffices to say that many soft laws have progressed into becoming hard law.

29.2.7 Drought-Related International Environmental Law

There are several international environmental laws that are drought related. Some are directed primarily at drought and can be regarded as primary drought related, while others are initiated to address causes, effects, and mitigation and can be regarded as secondary drought-related international law.

29.2.7.1 Primary Drought-Related International Law

The primary drought-related law could be found in the following:

1. *Agenda 21, Chapter 21 of the Rio de Janeiro Earth Summit of June 1992* in the Declaration on Environment and Development
2. *United Nations Convention to Combat Desertification, in those countries experiencing serious drought and desertification, particularly in Africa, of Paris 17 June 1994* (UNCCD)
3. *Hyogo Framework for Action 2005–2015: Building the resilience of nations and communities to disasters 2005*

29.2.7.1.1 Agenda 21, Chapter 12: Managing Fragile Ecosystems: Combating Desertification and Drought

Introduction

12.1 Fragile ecosystems are important ecosystems, with unique features and resources. Fragile ecosystems include deserts, semi-arid land, mountains, wetlands, small islands and certain coastal areas. Most of these ecosystems are regional in scope, as they transcend national boundaries. This chapter addresses land resource issues in deserts, as well as arid, semi-arid, and dry sub-humid areas. Sustainable mountain development is addressed in Chapter 13; small islands and coastal areas are discussed in Chapter 17.

12.2 Desertification is land degradation in arid, semi-arid, and dry sub-humid areas resulting from various factors, including climatic variations and human activities. Desertification affects about one sixth of the world's population, 70% of all drylands, amounting to 3.6 billion hectares, and one quarter of the total land area of the world. The most obvious impact of desertification, in addition to widespread poverty, is the degradation of 3.3 billion hectares of the total area of rangeland, constituting 73% of the rangeland with a low potential for human and animal carrying capacity; decline in soil fertility and soil structure on about 47 per cent of the dryland areas constituting marginal rainfed cropland; and the degradation of irrigated cropland, amounting to 30% of the dryland areas with a high population density and agricultural potential.

[*] European Soil Charter 1972.
[†] World Soil Charter 1981.
[‡] UNEP World Soil Policy 1982.
[§] Strategy on land use management and soil conservation 2004.

12.3 The priority in combating desertification should be the implementation of preventive measures for lands that are not yet degraded, or which are only slightly degraded. However, the severely degraded areas should not be neglected. In combating desertification and drought, the participation of local communities, rural organizations, national governments, non-governmental organizations and international and regional organizations is essential.

12.4 The following programme areas are included in this chapter:

a. Strengthening the knowledge base and developing information and monitoring systems for regions prone to desertification and drought, including the economic and social aspects of these ecosystems;
b. Combating land degradation through, inter alia, intensified soil conservation, afforestation and reforestation activities;
c. Developing and strengthening integrated development programmes for the eradication of poverty and promotion of alternative livelihood systems in areas prone to desertification;
d. Developing comprehensive anti-desertification programmes and integrating them into national development plans and national environmental planning;
e. Developing comprehensive drought preparedness and drought-relief schemes, including self-help arrangements, for drought-prone areas and designing programmes to cope with environmental refugees;
f. Encouraging and promoting popular participation and environmental education, focusing on desertification control and management of the effects of drought.*

29.2.7.1.2 United Nations Convention to Combat Desertification

The *United Nations Convention to Combat Desertification* (UNCCD) was adopted on October 14, 1994, and entered into force on December 26, 1996. The Convention builds on efforts undertaken in the past, including the 1977 United Nations Conference on Desertification and the Action Plan to combat desertification adopted at that Conference. The Convention is a fairly complex legal instrument that can only be outlined here.

29.2.7.1.2.1 Scope The major concern of the Convention is the conservation and management of land resources. It addresses primarily land degradation and its causes, and proposes actions to deal with the problem. However, the Convention goes beyond land degradation. Because of the interrelationship between land and water resources and their management, the Convention is at the same time an important instrument to conserve and manage water resources.

This is clear from the objective stated in Article 2 of the Convention:

- Combating desertification and mitigating the effects of drought
- Adopting "long-term integrated strategies that focus simultaneously, in affected areas, on improved productivity of land, and the rehabilitation, conservation and sustainable management of land and water resources, leading to improved living conditions, in particular at the community level."

29.2.7.1.2.2 Obligations The Convention again differentiates the obligations of

- All parties (Article 4)
- Affected country parties (Article 5)
- Developed country parties (Article 6)

All parties are required to adopt integrated approaches on combating desertification and drought and to cooperate internationally to achieve the objectives of the Convention. Affected country parties,

* Agenda 21, Chapter 12 Trans-boundary atmospheric pollution.

in addition, are required to give due priority to combating desertification and mitigating the effects of drought and allocate adequate resources to establish strategies and priorities, to address the underlying causes of desertification, and to promote the awareness and facilitate participation of local populations. Developed country parties, in addition, are required to actively support the efforts of affected developing country parties to provide substantial financial resources and other forms of support, to promote mobilization of new and additional fundings, to encourage mobilization of funding from the private sector, and to promote and facilitate access to appropriate technology.

29.2.7.1.2.3 Other Arrangements under the Convention The Convention regulates the details of the action programs that affected developing country parties are required to establish and implement. The action programs are further specified in region-specific Annexes to the Convention (Annex I: Africa; Annex II: Asia; Annex III: Latin America and the Caribbean; Annex IV: Northern Mediterranean).

Articles 20 and 21 deal with financial resources and mechanisms. All parties are required to make efforts to ensure adequate funding for the action programs provided under the Convention. The International Convention to combat desertification is a framework for mobilizing the cooperation, the financial means, and the transfer of technology necessary to initiate the action programs to Combat desertification and drought. It is a process-oriented legal instrument, the success of which may be seen only in the long term.

The first Conference of the Parties was held in 1997. It decided to establish the Secretariat of the Convention in Bonn, Germany, and allocate a $6.1 million budget for 2 years. It further decided that the global mechanism to provide information and additional financial resources would be managed by the International Fund for Agricultural Development, assisted by the UNDP and the World Bank. The Conference adopted the program of work of the Committee on Science and Technology. An important issue discussed concerned an additional Annex to the Convention dealing with problems of countries in transition.

29.2.7.1.2.4 National, Regional, and Subregional Action Programs National Action Programs (NAPs) are key instruments in the implementation of the Convention. They are strengthened by action programs on subregional and regional levels. NAPs are developed in the framework of a participative approach involving the local communities and they spell out the practical steps and measures to be taken to combat desertification in specific ecosystems. Access to all NAPs received so far by the UNCCD Secretariat from country parties to the different Regional Annexes to the Convention is ensured via the UNCCD website.

29.2.7.1.2.5 Regional Action Program (RAP) Guided by the principles and provisions of the Convention, especially those in its Annex II, the Regional Implementation Annex for Asia, Asian country parties, with continued assistance from the UNCCD Secretariat, initiated the development of the RAP in two important meetings: the Ministerial Conference on Regional Cooperation to Implement the UNCCD in Asia, Beijing 1997, and the International Expert Group Meeting on the Preparation of the Regional Action Program for Combating Desertification and Mitigating the Effects of Drought in Asia, Bangkok 1998. These meetings contributed to the formulation of a framework for the RAP and the development of NAPs.

Thematic Program Networks (*TPNs*) have been established in order to provide structural support to RAP and NAPs. There are six TPNs, coordinated by one task manager located in Asian countries, as follows:

- TPN 1 (China)—on desertification monitoring and assessment
- TPN 2 (India)—on agro-forestry and soil conservation in arid, semiarid, and dry subhumid areas
- TPN 3 (Islamic Republic of Iran)—on rangeland management in arid areas including the fixation of sand dunes
- TPN 4 (Syrian Arab Republic)—on water resources management for agriculture in arid, semiarid, and dry subhumid areas

- TPN 5 (Mongolia, yet to be launched)—on strengthening capacities for drought impact mitigating and desertification combating
- TPN 6 (Pakistan, yet to be launched)—on assistance for the implementation of integrated local area development programs initiatives

29.2.7.1.3 Hyogo Framework for Action 2005–2015: Building the Resilience of Nations and Communities to Disasters 2005

In order to achieve the goals and act upon the priorities identified in this framework, the following tasks have been identified to ensure implementation and follow-up by states, regional, and international organizations, in collaboration with civil society and other stakeholders. The ISDR partners, in particular the Inter-agency Task Force on Disaster Reduction and Secretariat, are requested to assist in implementing this framework for action:

- Implementation by different stakeholders.
- Multisectoral approach; participation of civil societies (NGOs, CBOs, volunteers), scientific community and private sector is vital. States primarily responsible; and enabling international environment is vital, including strengthened regional capacities; states, regional, and international organizations to foster coordination among themselves and a strengthened International Strategy for Disaster Reduction (ISDR).
- Build multistakeholder partnerships with particular attention to
  - Small-island developing states: Mauritius strategy
  - Least-developed countries
  - Africa
- Follow-up integrated with other major conferences in fields relevant to DRR; reviews as appropriate.
- Promote regional programs including for technical cooperation, capacity development, the development of methodologies and standards for hazard and vulnerability monitoring and assessment, the sharing of information and effective mobilization of resources; undertake and publish regional and subregional baseline assessments.
- Coordinate and publish reviews on progress and support needs, and assist countries in preparation of national summaries.
- Establish specialized regional collaborative centers.
- Support the development of regional mechanisms and capacities for early warning, including for tsunami.
- Develop a matrix of roles and initiatives in support of follow-up to the Hyogo framework.
- Facilitate the coordination of effective actions within the UN system and other international and regional entities to.
- Supporting the implementation of the, identify gaps, facilitate processes to develop guidelines and policy tools for each priority area.
- In broad consultation, develop generic, realistic, and measurable indicators. These indicators could assist states in measuring progress in the implementation of the; Hyogo framework, states regional organizations, and institutions.
- Engage in the implementation of the ISDR by encouraging integration of DRR into humanitarian and sustainable development fields.
- Strengthen the capacity of the UN system to assist disaster-prone developing countries in DRR and implement measures for assessment of progress.
- Identify actions to assist disaster-prone developing countries in the implementation of the, ensure their integration and that adequate funding is allocated; assist in setting up national strategies and programs for DRR.
- Integrate actions into relevant coordination mechanisms (UNDG, IASC, RCs, and UN Country Teams).

- Integrate DRR into development assistance frameworks such as CCA/UNDAF, PRSP.
- In collaboration with networks and platform support: data collection and forecasting on natural hazards and risks; early warning systems; full and open exchange of data.
- Support states with coordinated international relief assistance, to reduce vulnerability and increase capacities.
- Strengthen international mechanisms to support disaster-stricken states in post-disaster recovery with DRR approach.
- Adapt and strengthen interagency disaster management training for DRR and capacity building.

29.2.7.1.3.1 International Organizations (including UN System and IFIs)

ISDR (Inter-Agency Task Force on Disaster Reduction and secretariat)

- National baseline assessments of the status of DRR
- Publish and update a summary of national program for DRR including international cooperation
- Develop procedure for reviewing national progress including systems for cost–benefit analysis and ongoing monitoring on risk
- Consider acceding to, approving, or ratifying relevant international legal instruments and to make sure they are implemented
- Promote the integration of DRR with climate variability and climate change into DRR strategies and adaptation to climate change
- Ensure management of risks to geological hazards
- Design national coordination mechanisms for the implementation and follow-up
- Communicate to the ISDR secretariat
- Mobilize resources and capabilities of relevant national, regional, and international bodies, including the UN system
- Provide and support the implementation of the HFA in disaster-prone developing countries, including through financial and technical assistance, addressing debt sustainability, technology transfer, public–private partnership, and north–south and south–south cooperation
- Mainstream DRR measures into multilateral and bilateral development assistance programs; ISDR
- Support national platforms and regional coordination
- Register relevant partnerships with Commission on Sustainable Development
- Stimulate the exchange, compilation, analysis, and dissemination of best practices, lessons learnt
- Prepare periodic review on progress toward achieving the goals objectives of the and provide reports to the UNGA and other UN bodies

In order to achieve the goals and act upon the priorities identified in this framework, the following tasks have been identified to ensure implementation and follow-up by states, regional, and international organizations in collaboration with civil society and other stakeholders. The ISDR partners, in particular the Inter-agency Task Force on Disaster Reduction and secretariat, are requested to assist in implementing this framework for action; provide adequate voluntary financial contribution to the UN Trust Fund for DR to support follow-up activities to review usage and feasibility for the expansion of this fund, develop partnership to implement schemes that spread out risks, reduce insurance premiums, expand insurance coverage, and increase financing for post-disaster reconstruction, including through public and private partnerships, and promote an environment that encourages a culture of insurance in developing countries.

29.2.7.1.4 The Sendai Framework for Disaster Risk Reduction 2015–2030

The Sendai Framework for Disaster Risk Reduction 2015–2030 is the Successor Instrument to the *Hyogo Framework for Action* (*HFA*) *2005–2015: Building the Resilience of Nations and Communities to Disasters*

It was adopted on March 18, 2015, at the World Conference on Disaster Risk Reduction held in Sendai, Japan. The Sendai Framework is the outcome of stakeholder consultations initiated in March 2012 and intergovernmental negotiations held from July 2014 to March 2015, which were supported by the UNISDR upon the request of the UN General Assembly. UNISDR has been tasked to support the implementation, follow-up, and review of the Sendai Framework. DRR aims to reduce the damage caused by natural hazards like earthquakes, floods, droughts, and cyclones, through an ethic of prevention. There is no such thing as a "natural" disaster, only natural hazards.

The Sendai Framework for Disaster Risk Reduction 2015–2030 was adopted at the Third United Nations World Conference on Disaster Risk Reduction, held from March 14 to 18, 2015 in Sendai, Miyagi, Japan, which represented a unique opportunity for countries:

- To adopt a concise, focused, forward-looking, and action-oriented post-2015 framework for disaster risk reduction
- To complete the assessment and review of the implementation of the Hyogo Framework for Action 2005–2015: building the Resilience of Nations and Communities to Disasters
- To consider the experience gained through the regional and national strategies/institutions and plan for disaster risk reduction and their recommendations, as well as relevant regional agreements for the implementation of the Hyogo Framework for Action
- To identify modalities of cooperation based on commitments to implement a post-2015 framework for disaster risk reduction
- To determine modalities for the periodic review of the implementation of a post-2015 framework for disaster risk reduction

29.2.7.2 Secondary Drought-Related International Environmental Laws

The secondary drought-related international environmental laws can be grouped under laws of

1. Air pollution
2. Water resources management
3. Soil degradation
4. Human rights
5. Biological diversity

29.2.7.2.1 Conventions on Air Pollution

- *Agenda 21 Chapter 9D Trans-boundary Atmospheric Pollution*[*]
- *1977 The Geneva Convention on Long-Range Trans-boundary Air Pollution and its Protocols*[†]
- *1985 Vienna Framework Convention for the Protection of the Ozone Layer*[‡]
- *1987 Montreal Protocol in Substances that Deplete the Ozone Layer*[§]
- *1992 United Nations Framework Convention on Climate Change (UNFCCC)*[¶]
- *1997 Kyoto Protocol on Reduction of Green House Gases*[**]

Although air pollution sometimes may be a local phenomenon, it is clear that it is essentially an international problem. Pollutants may be transported over long distances. Impacts of air pollution may occur some 1000 km away from the sources. Therefore, air pollution clearly needs an international response. States need to agree on measures to reduce existing and to prevent further air pollution. Agreement may be laid down in political but also in legal instruments. Examples are the Geneva Convention and its Protocols, which are dealt with subsequently in detail. An international political consensus can also be found in the 1992 Rio Conference Agenda 21, Chapter 9.

[*] Agenda 21, Chapter D Trans-boundary atmospheric pollution.
[†] The Geneva Convention on Long Range Trans-boundary Air Pollution and its Protocol, 1979.
[‡] Vienna Framework Convention for the Protection of the Ozone layer, 1985.
[§] Montreal Protocol on Substances that deplete the ozone layer, 1987.
[¶] United Nations Framework Convention on Climate Change (UNFCC), 1992.
[**] Kyoto Protocol on Reduction of Greenhouse gases, 1997.

29.2.7.2.1.1 Agenda 21, Chapter 9D: Trans-Boundary Atmospheric Pollution

Basis for Action

9.25 Trans-boundary air pollution has adverse health impacts on humans and other detrimental environmental impacts, such as tree and forest loss and the acidification of water bodies. The geographical distribution of atmospheric pollution monitoring networks is uneven, with the developing countries severely underrepresented. The lack of reliable emissions data outside Europe and North America is a major constraint to measuring trans-boundary air pollution. There is also insufficient information on the environmental and health effects of air pollution in other regions.

9.26 The 1979 Convention on Long-range Trans-boundary Air Pollution and its protocols have established a regional regime in Europe and North America, based on a review process and cooperative programmes for systematic observation of air pollution, assessment and information exchange. These programmes need to be continued and enhanced, and their experience needs to be shared with other regions of the world.

Objectives

9.27 The objectives of this programme are:

a. To develop and apply pollution control and measurement technologies for stationary and mobile sources of air pollution and to develop alternative environmentally sound technologies;
b. To observe and assess systematically the sources and extent of trans-boundary air pollution resulting from natural processes and anthropogenic activities;
c. To strengthen the capabilities, particularly of developing countries, to measure, model and assess the fate and impacts of trans-boundary air pollution, through, inter alia, exchange of information and training of experts;
d. To develop capabilities to assess and mitigate trans-boundary air pollution resulting from industrial and nuclear accidents, natural disasters and the deliberate and/or accidental destruction of natural resources;
e. To encourage the establishment of new and the implementation of existing regional agreements for limiting trans-boundary air pollution;
f. To develop strategies aiming at the reduction of emissions causing trans-boundary air pollution and their effects.

Activities

9.28 Governments at the appropriate level, with the cooperation of the relevant United Nations bodies, and, as appropriate, intergovernmental and nongovernmental organizations, the private sector and financial institutions, should:

a. Establish and/or strengthen regional agreements for trans-boundary air pollution control and cooperate, particularly with developing countries, in the areas of systematic observations and assessment, modeling and the development and exchange of emissions control technologies of mobile and stationary sources of air pollution. In this context, greater emphasis should be put on addressing the extent, causes, health and socio-economic impacts of ultraviolet radiation, acidification of the environment and photo-oxidant damage to forests and other vegetation;
b. Establish or strengthen early warning systems and response mechanisms for trans-boundary air pollution resulting from industrial accidents and natural disasters and the deliberate and/or accidental destruction of natural resources;
c. Facilitate training opportunities and exchange of data, information and national and/or regional experiences;

TABLE 29.2 List of Chemical Substances Capable of Modifying the Chemical and Physical Protection of the Ozone Layer

The following chemical substances of natural and anthropogenic origin, not listed in order of priority, are thought to have the potential to modify the chemical and physical protection of the ozone layer.

a. Carbon substances i. Carbon monoxide (CO) ii. Carbon dioxide (CO_2) iii. Methane (CH_4) iv. Non-metals hydrocarbon species	c. Chlorine substances i. Fully halogenated alkanes, e.g., CCI_4, $CFCI_3$ (CFC-11), CF_2CI_2 (CFC-12), $C_2F_3Cl_3$ (CFC-113), $C_2F_4CI_2$ (CFC-114) ii. Partially halogenated alkanes, e.g., CH_3CI, CHF_2CI (CFC-22), CH_3CCI_3, $CHFCI_2$ (CFC-2l) d. Bromine substances Fully halogenated alkanes, e.g., CF_3Br
b. Nitrogen substances i. Nitrous oxide (N_2O) ii. Nitrogen oxides (NO_X)	e. Hydrogen substances i. Hydrogen (H_2) ii. Water (H_2O)

Source: Convention for the Protection, of the Ozone Layer of 22 March 1985, Annex I, para. 4.*

d. Cooperate on regional, multilateral and bilateral bases to assess trans-boundary air pollution, and elaborate and implement programmes identifying specific actions to reduce atmospheric emissions and to address their environmental, economic, social and other effects (Table 29.2).

CFCs are used as propellants and solvents in aerosol sprays, fluids in refrigeration and air conditioning equipment, foam-blowing agents in plastic foam production, and solvents mainly in the electronic industry. In addition to CFCs, bromine emissions can also damage the ozone layer. Bromine emissions result, for example, from halons used in fire extinguishers. The reduction of the ozone in the stratosphere has impacts on human, animal, and plant life. The most serious impacts on human life are the negative impacts on the human immune system and the possible increase in skin cancers and other diseases—for example, blindness. Plants are sensitive to ultraviolet radiation and ultraviolet radiation may kill aquatic organisms, particularly microorganisms, which indicates that there may be effects on fisheries and also on natural water purification processes. The reduction of the ozone layer may even result in climate change.

29.2.7.2.1.2 The Geneva Convention on Long-Range Trans-Boundary Air Pollution and Its Protocols The Geneva Convention on Long-Range Trans-boundary Air Pollution and its protocols, developed within the UNECE, comprising all the European states including the Russian Federation and some of the Commonwealth of Independent States countries as well as Canada and the United States. It is a regional treaty system; however, it covers the area of highly industrialized countries living together in a fairly narrow geographical context.

The development of the convention and the protocols must be seen against the background of two major international developments. One is the intensive discussion in the 1970s about damage from air pollution, which was clearly related to trans-boundary transport of air pollutants. The second important factor leading to the convention and its protocols was the process of political cooperation in Europe, which began with the 1975 Helsinki Conference on Security and Cooperation in Europe.

The Helsinki Final Act of 1975 contained also a framework for environmental cooperation in Europe, particularly with regard to air pollution. Therefore, immediately after 1975, negotiations began on a convention on air pollution control. On November 13, 1979, the convention was signed in Geneva by the UNECE countries. It was designed as a framework convention to be implemented by more specific instruments (protocols). This framework convention/protocols approach was suggested in order to deal with the complex problems of air pollution. Air pollution is caused by a variety of air pollutants resulting from a variety of processes and products. Pollutants are transported across boundaries, and the countries involved have different economic, social, political, and cultural conditions. Therefore, the 1979 Geneva

* Convention for the Protection of the Ozone layer, March 22, 1985, Annex I, para. 4.

Convention provided a set of basic obligations; more specific rules and regulations were laid down in subsequent protocols.*

December 2004 marked 25 years since the adoption of the Geneva Convention, and it can be considered as a highly effective treaty system. A series of legal instruments could be worked out and implemented that forced states to take action against air pollution, as well as joint action at regional and subregional levels.

The System of the 1979 Geneva Convention on Long-Range Trans-boundary Air Pollution 1979 Convention on Long-Range Trans-boundary Air Pollution; 32 signatories and 49 ratifications, entered into force on March 16, 1983.

The Convention has been extended by eight protocols:

1. *1999 Protocol to Abate Acidification, Eutrophication, and Ground-level Ozone*; 31 signatories and 16 ratifications, entered into force on May 17, 2005
2. *1998 Protocol on Persistent Organic Pollutants (POPs)*; 22 ratifications parties, entered into force on October 23, 2003
3. *1998 Protocol on Heavy Metals*; 24 ratifications parties, entered into force on December 29, 2003
4. *1994 Protocol on Further Reduction of Sulphur Emissions*; 25 parties, entered into force on August 5, 1998
5. *1991 Protocol concerning the Control of Emissions of Volatile Organic Compounds or their Trans-boundary Fluxes*; 21 parties, entered into force on September 29, 1997
6. *1988 Protocol concerning the Control of Nitrogen Oxides or their Trans-boundary Fluxes*; 29 parties, entered into force on February 14, 1991
7. *1985 Protocol on the Reduction of Sulphur Emissions or their Trans-boundary Fluxes by at least 30%*; 22 parties, entered into force on September 2, 1987
8. *1984 Protocol on Long-term Financing of the EMEP*; 41 parties, entered into force on January 28, 1988

> *1985 Protocol*: The Parties shall reduce their national annual sulphur emissions or their trans-boundary fluxes by at least 30% as soon as possible and at the latest by 1993, using 1980 levels as the basis for calculation of reductions.
>
> Article 2, Protocol on the Reduction of Sulphur Emission (1985)
>
> *1994 Protocol*: The Parties shall control and reduce their sulphur emissions in order to protect human health and the environment from adverse effects, in particular acidifying effects, and to ensure, as far as possible, without entailing excessive costs, that depositions of oxidized sulphur compounds in the long term do not exceed critical loads for sulphur given, in annex I, as critical sulphur depositions, in accordance with present scientific knowledge.
>
> As a first step, the Parties shall, as a minimum, reduce and maintain their annual sulphur emissions in accordance with the timing and levels specified in annex U.
>
> (Article 2, para. 2, Protocol on further Reduction of Sulphur Emissions, 1994)

29.2.7.2.1.3 The Vienna Convention for the Protection of the Ozone Layer The Vienna Convention for the Protection of the Ozone Layer was adopted on March 22, 1985, and entered into force on September 22, 1988. The obligations under the convention in Article 2 are as follows:

- Parties shall take appropriate measures to protect human health and the environment against adverse effects resulting or likely to result from human activities that modify or are likely to modify the ozone layer.
- Parties shall cooperate by means of systematic observations, research, and information exchange in order to better understand and assess the effects of human activities on the ozone layer and the effects of human health and the environment from modifications of the ozone layer.

* Helsinki Final Act of 1975.

- Parties shall adopt appropriate legislative or administrative measures and cooperate in harmonizing appropriate policies to control, limit, reduce, or prevent human activities under their jurisdiction and control, should it be found that these activities have or are likely to have adverse effects resulting from modification or likely modification of the ozone layer.
- Parties shall cooperate in the formulation of agreed measures, procedures, and standards for the implementation of this convention, with a view to the adoption of protocols and annexes.
- Parties shall cooperate with competent international bodies to implement effectively the convention and protocols to which they are a Party.

The remaining parts of the convention concern cooperation in research and systematic observations, cooperation in the legal, scientific, and technical field, and institutional matters. Annex 1 on research and systematic observations is especially important because paragraph 4 lists the substances that have the potential to modify the chemical and physical property of the ozone layer. The annex was important because it focused the subsequent negotiations on the Montreal Protocol. Therefore, at least the subject for the coming negotiations had been determined.

29.2.7.2.1.4 The 1987 Montreal Protocol on Substances that Deplete the Ozone Layer The Montreal Protocol on Substances that Deplete the Ozone Layer was adopted on September 16, 1987, and entered into force on January 1, 1989. By 1997, the protocol was in force for 161 parties. The protocol is a separate international legal instrument. However, Article 16 of the 1985 convention provides that a state or a regional economic integration organization may not become a party to a protocol unless it is or becomes at the same time a party to the convention.

The protocol contains a list of substances that may deplete the ozone layer and therefore need to be controlled (Table 29.3).

The protocol provides for obligations to freeze the consumption and the production of controlled substances and provides for the obligation to reduce the consumption and production at least for part of the substances (Table 29.4).

TABLE 29.3 List of Substances That May Deplete the Ozone Layer and Therefore Need to Be Controlled

List of Controlled Substances		
Groups	Substances	Ozone-Depleting Potential[a]
Group I	$CFCI_3$ (CFC-11)	1.0
	CF_2CI_2 (CFC-12)	1.0
	$C_2F_3CI_3$ (CFC-1 13)	0.8
	$C_2F_4CI_2$ (CFC-l 14)	1.0
	C_2F_5CI (CFC-1 15)	0.6
Group II	CF_2BrCI (halon-1211)	3.0
	CF_3Br (halon-1301)	10.0
	$C_2F_4Br_2$ (halon-2402)	(to be determined)

[a] The ozone-depleting potentials are estimates based on existing knowledge and will be reviewed and revised periodically.

TABLE 29.4 The Freeze and Reduction Obligations of Montreal Protocol

Montreal Protocol 1987		
Control Measure	Substances Group I	Substances Group II
Freeze of consumption and production at 1986 levels	July 1, 1990	January 1, 1993
Reduction by 20% of consumption and production	July 1, 1994	
Reduction by 50% of consumption and production	July 1, 1999	

From 1986, levels of these substances should be determined and the scope , amount and timing of any such adjustment and reduction should be proposed. In taking the decisions on adjustments, the parties are required to make all efforts to reach consensus. If consensus fails, decisions are taken by a two-thirds majority vote. Decisions are binding on all parties and enter into force after 6 months from the date of communication.

Adjustments and Amendments to the Montreal Protocol

- *London Amendment*
  The London Amendment was adopted in 1990 at the Second Meeting of the Parties to the Montreal Protocol held in London. The amendment introduced control measures for both production and consumption for three new groups of substances, namely other halogenated CFCs (Annex B, Group I substances), carbon tetrachloride (Annex B, Group II), and methyl chloroform or 1,1,1–trichloroethane (Annex B, Group III). Control measures also included restrictions on trade with non-parties.

  The financial mechanism was also established (Article 10 of the Protocol) for providing financial and technical assistance to developing countries to enable their compliance with their obligations under the protocol. The financial mechanism meets the agreed incremental costs of developing countries in order to enable their compliance with the control measures of the protocol.

  The amendment further introduced HCFCs (Annex C, Group I substances) but only required reporting of production and consumption data for the Annex and did not introduce control measures for the Annex Group.

  The London Amendment entered into force on August 10, 1992.

- *Copenhagen Amendment*
  The Copenhagen Amendment was adopted in 1992 at the Fourth Meeting of the Parties to the Montreal Protocol held in Copenhagen. The amendment introduced control measures for HCFCs' consumption only (Annex C, Group I substances) and for both production and consumption for two new groups of substances, namely HBFCs (Annex C, Group II substances) and Methyl Bromide (Annex E, Group I).

  The Copenhagen Amendment entered into force on June 14, 1994.

  CFCs are being replaced by HFCs, which have a large global warming potential. The Kyoto Protocol on climate change has included HFCs in the basket of six gases whose emissions are to be reduced by the industrialized countries. Are the two global protocols sending confusing signals? Does the Kyoto Protocol hinder the implementation of the Montreal Protocol? The parties to the Montreal Protocol as well as the parties to the Climate Change Convention now have the reports of their scientific and technical panels on how to minimize the emissions of HFCs. Implementation of the panels' recommendations by governments is important.

29.2.7.2.1.5 The 1992 United Nations Framework Convention on Climate Change (UNFCCC)

Overview: The convention, which entered into force on March 21, 1994, contains rather complex provisions; therefore, an overview may be appropriate, starting with the objective and followed by a set of principles that guide the application and the development of further legal instruments dealing with climate change. The commitments laid down in the convention follow the concept of "common but differentiated responsibilities." The convention provides for cooperation in research and systematic observation and lays down obligations for education, training, and public awareness. It also introduces a complicated institutional mechanism; Conference of the Parties; secretariat; subsidiary body for scientific and technical advice; subsidiary body for implementation; and a financial mechanism. In addition, the convention is an active rather than static instrument that can respond to changing needs and situations through amendments, annexes, and protocols.

Objective: The objective of the Convention is described as follows (Article 2):

> The ultimate objective of this Convention and any related legal instrument that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time flame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.

This provision on the objective of the convention merits some reflection. The convention recognizes that the prevention of dangerous interference with the climate system is necessary. However, the underlying understanding is that the objective may be achieved after a certain time and that it is not necessary to prevent all changes of a climate system. Changes may be possible and they may be acceptable. It is believed that ecosystems may adapt naturally to climate change. Therefore, "prevention of dangerous anthropogenic interference with the climate system" does not imply the prevention of climate change.

The reference to sustainable development and to food production, which must not be threatened, is not an excuse for continuing with "business as usual." First, economic development needs to take place in a sustainable manner. Second, it is clear from the introductory chapter of this course that climate change may be possible and that climate change may have serious consequences, which may affect in a negative way economic development and food production. Therefore, the conclusion clearly is that parties may have to take measures to prevent climate change in order to secure food production and sustainable development.

Principles: The convention sets out a number of principles that give a general orientation for further interpretation of the convention and further development of legal instruments. It is interesting and somehow unusual that the convention uses the language of recommendations ("should"). The principles set out in Article 3 are as follows:

- The parties should protect the climate system for the benefit of present and future generations of humankind on the basis of equity and in accordance with the common but differentiated responsibilities and respective capabilities.
- The specific needs and special circumstances of developing country parties should be given full consideration.
- The parties should take precautionary measures to anticipate, prevent, or minimize the causes of climate change and mitigate its adverse effects.
- The parties have a right to, and should, promote sustainable development.
- The parties should cooperate to promote a supportive and open international economic system that would lead to sustainable economic growth and development in all parties, particularly developing country parties.

Common but Differentiated Responsibilities under the UNFCCC: Preamble: Acknowledging that the global nature of climate change calls for the widest possible cooperation by all countries and their participation in an effective and appropriate international response, in accordance with their common but differentiated responsibilities and respective capabilities and their social and economic conditions.

> Article 3, Principle No. I: Parties should protect the climate system for the benefit of present and future generations of humankind, on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities. Accordingly, developed country Parties take the lead in combating climate change and the adverse effects thereof.
>
> Article 4, Commitments, paragraph I: All Parties, taking into account their common but differentiated responsibilities and their specific national and regional development priorities, objectives, and circumstances, shall…

Accordingly, Article 4 on the commitments of the convention differentiates between the various categories of parties. The differentiated commitments are as follows.

Commitments of all parties (Article 4. Para. 8. Para. 9. Para 10) include

- Developing and updating national inventories of anthropogenic emissions of all greenhouse gases
- Formulating, implementing, publishing, and regularly updating national and regional programs containing measures to mitigate climate change
- Promoting and cooperating in the development, application, and diffusion, including transfer, of technologies, practices, and processes that control, reduce, or prevent anthropogenic emissions of greenhouse gases
- Promoting sustainable management and promoting and cooperating in the conservation and enhancement of sinks and reservoirs of all greenhouse gases

Other major provisions of the Kyoto Protocol concern joint implementation and emissions trading. As far as these instruments are concerned, the protocol contains principles and passes the responsibility of the details to the next Conference of the Parties. The fact that the instruments require more work on details may lead to difficulties in the application of the protocol. The complexity of the negotiations, however, meant that considerable "unfinished business" remained even after the Kyoto Protocol itself was adopted. The protocol sketched out the basic features of its "mechanisms" and compliance system, for example, but did not flesh out the all-important rules of how they would operate. A new round of negotiations was therefore launched to flesh out the Kyoto Protocol's rulebook, conducted in parallel with negotiations on ongoing issues under the convention. This round finally culminated at the Seventh Conference of Parties with the adoption of the Marrakesh Accords, setting out detailed rules for the implementation of the Kyoto Protocol. As discussed, the Marrakesh Accords also took some important steps forward regarding the implementation of the convention.

In fall 2004, with the decision of the Russian Federation to ratify the Kyoto Protocol, the minimum requirements for its entry into force were finally met: in addition to the 55 states ratifying the protocol, these states must account for 55% of the world's greenhouse gas emissions. The Kyoto Protocol entered into force on February 16, 2005.

29.2.7.2.1.6 Reduction of Greenhouse Gases (Article 3) Obligations to reduce greenhouse gases apply to countries included in Annex I of the convention (mentioned earlier). The greenhouse gases to be reduced are listed in Annex A of the Kyoto Protocol; they include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydro-fluorocarbons (HFCs), per-fluorocarbons) and sulfur hexafluoride. The protocol differentiates between Annex I countries and provides specific reduction targets for individual countries or groups of countries. Generally, the protocol says that Annex I countries, as a group must reduce their emissions of the specified greenhouse gases by 5% between 2008 and 2012. The year of reference is 1990; for the last three mentioned gases in Annex A, the parties may specify 1995 instead.

Three countries—Australia, Iceland, and Norway—are allowed to increase their emissions. New Zealand, the Russian Federation, and Ukraine are obliged to freeze their emissions at the level of the base years.

29.2.7.2.2 Water Resource Management

Protection of the Quality and Supply of Freshwater Resources: Application of Integrated Approaches to the Development, Management, and Use of Water Resources

Freshwater resources are an essential component of the Earth's hydrosphere and an indispensable part of all terrestrial ecosystems. The freshwater environment is characterized by the hydrological cycle, including floods and droughts, which in some regions have become more extreme and dramatic in their consequences. Global climate change and atmospheric pollution could also have an impact on freshwater resources and their availability and, through sea-level rise, threaten low-lying coastal areas and small island ecosystems. Water is needed in all aspects of life. The general objective is to make certain that adequate supplies of water of good quality are maintained for the entire population of this planet, while preserving the hydrological, biological, and chemical functions of ecosystems, adapting human activities within the capacity limits of nature and combating vectors of water-related diseases. Innovative technologies, including the improvement of indigenous technologies, are needed to fully utilize limited water resources and to safeguard those resources against pollution.

The widespread scarcity, gradual destruction, and aggravated pollution of freshwater resources in many parts of the world, along with the progressive encroachment of incompatible human activities, demand integrated water resources planning and management. There is probably little controversy about the recognition of these rules. They have emerged in state practice and are evident in international conventions as well as in declarations and resolutions of international organizations. They are expressed and elaborated in a series of resolutions of professional legal associations such as the International Law Association, and are generally recognized in international judicial decisions.

1. *The Helsinki Rules*
   A milestone in the development of international water law was the establishment of the Helsinki Rules of the International Law Association adopted at its 1966 session. Since they are always referred to and cited, the Helsinki Rules are reproduced herein.

International Law Association/Helsinki Rules on the Uses of the Waters of International Rivers

Chapter 1: General

Article I
The general rules of international law as set forth in these chapters are applicable to the use of the waters of an international drainage basin except as may be provided otherwise by convention, agreement or binding custom among the basin states.

Article II
An international drainage basin is a geographical area extending over two or more states determined by the watershed limits of the system of waters, including surface and underground waters, flowing into a common terminus.

Article III
A "basin state" is a state, which includes a portion of an international drainage basin.

Equitable Utilization of the Waters of an International Drainage Basin

Article IV
Each basin state is entitled, within its territory, to a reasonable and equitable share in the beneficial uses of the waters of an international drainage basin.

Article V

1. The reasonable and equitable share within the meaning of Article IV is to be determined in the light of all relevant factors in each particular case.
2. Relevant factors that are to be considered include, but are not limited to:
   (a) The geography of the basin, including in particular the extent of the drainage area in the territory of each basin state;
   (b) The hydrology of the basin, including in particular the contribution of water by each basin state;
   (c) The climate affecting the basin;
   (d) The past utilization of the waters of the basin, including in particular existing utilization;
   (e) The economic and social needs of each basin state;
   (f) The population dependent on the waters of the basin in each basin state;
   (g) The comparative costs of alternative means of satisfying the economic and social needs of each basin state;
   (h) The availability of other resources;

(i) The avoidance of unnecessary waste in the utilization of waters of the basin;
(j) The practicability of compensation to one or more of the co-basin states as a means of adjusting conflicts among uses;
(k) The degree to which the needs of a basin state may be satisfied, without causing substantial injury to a co-basin state.

3. The weight to be given to each factor is to be determined by its importance in comparison with all other relevant factors. In determining what is a reasonable and equitable share, all relevant factors are to be considered together and a conclusion reached on the basis of the whole.

Article VI
A use or category of uses is not entitled to any inherent preference over any other use or category of uses.

Article VII
A basin state may not be denied the present reasonable use of the waters of an international drainage basin to reserve for a co-basin state a future use of such waters.

Article VIII

1. An existing reasonable use may continue in operation unless the factors justifying its continuance are outweighed by other factors leading to the conclusion that it be modified or terminated so as to accommodate a competing incompatible use.
2. (a) A use that is in fact operational is deemed to have been an existing use from the time of the initiation of construction directly related to the use or, where such construction is not required, the undertaking of comparable acts of actual implementation.
   (b) Such a use continues to be an existing use until time as it is discontinued with the intention that it be abandoned.
3. A use will not be deemed an existing use if at the time of becoming operational it is incompatible with an already existing reasonable use.

Chapter 3: Pollution

Article IX
As used in this chapter, the term "water pollution" refers to any detrimental change resulting from human conduct in the natural composition, content or quality of the waters of an international drainage basin.

Article X

1. Consistent with the principle of equitable utilization of the waters of an international drainage basin, a state:
   (a) Must prevent any new form of water pollution or any increase in the degree of existing water pollution in an international drainage basin that would cause substantial injury in the territory of a co-basin state, and
   (b) Should take all reasonable measures to abate existing water pollution in an international drainage basin to such an extent that no substantial damage is caused in the territory of a co-basin state.
2. The rule stated in paragraph 1 of this article applies to water pollution originating:
   (a) Within a territory of the state, or
   (b) Outside the territory of the state, if it is caused by the state's conduct.

Established at Helsinki (August 20, 1966)

In 2004, the International Law Association (ILA) revised the Helsinki Rules and other ILA rules on international water resources. At the same time, the Berlin Rules on Water Resources were adopted. These rules reflect the existing state of customary law on water resources, taking into account the developments that have occurred since the adoption of the Helsinki Rules, including the development of conventions and the decisions of international tribunals. As the ILA Report on the Berlin Rules states: The Rules are both, the recognition of existing law and to some extent, a progressive development of international law.

The Berlin Rules, which apply to all types of freshwater including surface waters and groundwater, follow a holistic approach to water resource management. They include rules on all waters and rules on internationally shared waters (which were the main concern of the international freshwater law so far). The rules include rights of individuals, in particular the recognition of the right to access to water and the right to information and participation. The rules address the principles of protection of aquatic environments including the principles of ecological integrity and the precautionary principle. The rules also address issues of navigation and thus have a much broader scope than the international rules so far [7].

Codification of International Law Concerning Freshwater Resources

1. *United Nations International Law Commission/Convention on Non-Navigational Uses of International Watercourses*

In the 1970s, the International Law Commission started work on the codification of the law on non-navigational uses of international watercourses. Draft articles were adopted at the 46th Session of the International Law Commission on June 24, 1994. The General Assembly of the United Nations on May 21, 1997, adopted draft articles as the Convention on the Law of the Non-Navigational Uses of International Watercourses. As of May 2005, the convention has been signed by 16 states; 12 states ratified or acceded to it. The convention has not yet entered into force.

Scope and Definition
The convention applies to the uses of international watercourses and of their waters for purposes other than navigation, and to measures of conservation and management related to the uses of those watercourses and their waters. Navigation is regulated only to the extent that other uses affect navigation or are affected by navigation. The definition of "watercourse" is fairly broad; it means "a system of surface waters and ground waters constituting by virtue of their physical relationship a unitary whole and normally flowing into a common terminus" (Article 2).

Agreements between Watercourse States
The convention provides that it does not affect the rights or obligations from existing agreements (Article 3(1)); however they may be harmonized with the provisions of the convention (Article 3(2)). Furthermore, watercourse states may conclude more specific "watercourse agreements which apply and adjust the provisions of the present Convention to the characteristics and uses of a particular international watercourse or part thereof" (Article 3(3)). The convention does not require parties to conclude additional and more specific "watercourse agreements"; it rather requires consultations and negotiations in good faith for the purpose of concluding a watercourse agreement or agreements ("pactum de negotiando") where a watercourse state considers that adjustment and application of the provisions of the convention are needed (Article 3(5)).

Principles
Most important is the attempt to specify the principle of equitable and reasonable utilization.

Convention on the Law of Non-Navigational Uses of International Watercourses
Article 5—Equitable and reasonable utilization and participation

1. Watercourse states shall in their respective territories utilize an international watercourse in an equitable and reasonable manner. In particular, an international watercourse shall be used and developed by watercourse states with a view to attaining optimal and sustainable utilization thereof and benefits there from, taking into account the interests of the watercourse states concerned, consistent with adequate protection of the watercourse.

2. Watercourse states shall participate in the use, development, and protection of an international watercourse in an equitable and reasonable manner. Such participation includes both the right to utilize the watercourse and the duty to cooperate in the protection and development thereof, as provided in the present convention.

Article 6—Factors relevant to equitable and reasonable utilization

1. Utilization of an international watercourse in an equitable and reasonable manner within the meaning of Article 5 requires taking into account all relevant factors and circumstances, including
   (a) Geographic, hydrographic, hydrological, climatic, ecological, and other factors of a natural characters
   (b) The social and economic needs of the watercourse states concerned
   (c) The population dependent on the watercourse in each watercourse state
   (d) The effects of the use or uses of the watercourses in one watercourse state on other watercourse states
   (e) Existing and potential uses of the watercourse
   (f) Conservation, protection, development, and economy of use of the water resources of the watercourse and the costs of measures taken to that effect
   (g) The availability of alternatives, of comparable value, to a particular planned or existing use
2. In the application of Article 5 or paragraph 1 of this article, watercourse states concerned shall, when the need arises, enter into consultations in a spirit of cooperation

Prevention of Harmful Conditions (*Part IV of the Convention*)
Watercourse states are obliged to take individual or joint measures to prevent or mitigate impacts that may be harmful to other watercourse states, whether resulting from natural causes or human conduct (Article 27). This obligation may be considered as the recognition of the principle of precautionary action. In cases of emergency situations, watercourse states must immediately notify other potentially affected states and competent international organizations and take all practicable measures necessitated by the circumstances to prevent, mitigate, and eliminate harmful effects of the emergency (Article 28).*

United Nations Economic Commission for Europe (*UNECE*)
The UNECE has undertaken remarkable activities in the field of international management of water resources. It has adopted various soft-law (non-legally binding) instruments concerning the matter and, in 1992, the Convention on the Protection and Use of Trans-boundary Watercourses and International Lakes.

On April 23, 1980, the Declaration of Policy on Prevention and Control of Water Pollution including Trans-boundary Pollution was adopted. It is a broad instrument applying to water resource management in general, not only to trans-boundary management. On April 22, 1988, the Commission adopted the Decision on Cooperation in the Field of Environment Protection of Water Resources. On June 1, 1989, the Charter on Ground Water Management was adopted. Finally, on June 1, 1990, a Code of Conduct on Accidental Pollution of Trans-boundary Inland Waters was adopted.

UNECE Convention on the Protection and Use of Trans-boundary Watercourses and International Lakes (*Helsinki Convention*)

The convention was adopted on March 17, 1992, and entered into force on October 6, 1996.

The convention was amended in 2003 by Decision of the Parties in order to allow states from outside the area of the UNECE to become parties to the convention. So far, these amendments have been ratified by two states; 23 ratifications or accession are necessary for the entry into force.

* Convention on the Law of Non-Navigational Uses of International Watercourses.

The convention differentiates between obligations for all parties, on the one hand, and riparian parties, on the other. Obligations for all parties include the "standard" requirements, such as the prevention, control, and reduction of pollution, the monitoring of the conditions of trans-boundary waters and cooperation in research and development, and exchange of information. In the context of trans-boundary pollution, the convention speaks of the prevention, control, and reduction of any trans-boundary impact and defines "impact" as "significant adverse effect on the environment" (Article 1, para. 2). The control obligations are specified in Articles 2 and 3; reference is made to the precautionary principle, the polluter-pays principle and the principle of intergenerational equity (Article 2, para. 5). Most useful are the definition of "best available technology," the guidelines for "best environmental practices," and "water quality objectives and criteria."

Obligations for riparian states are stricter than under the United Nations Convention. According to Article 9 of the UNECE convention, riparian states are obliged to enter into bilateral or multilateral "agreements or other arrangements" (Article 9, para 1). Riparian states have a duty to provide for the establishment of joint bodies (Article 9, para. 2). They have a duty to hold consultations (Article 10). Further, they have a duty to establish and implement joint monitoring programs and to cooperate in research and development and exchange of information.

- Recommendations to ECE Governments on Rational Use of Water in Industrial Processes, 1987 (ECE/ENVWA/2)
- Recommendations to ECE Governments on Water-Management Systems, 1987 (ECE/ENVWA/2)
- ECE Declaration of Policy on the Rational Use of Water, 1984 (ECE/ENVWA/2)
- Recommendations to ECE Governments on Drinking Water Supply and Effluent Disposal System, 1982 (ECE/ENVWA/2)
- Recommendations to ECE Governments on Water Pollution from Animal Production, 1981 (ECE/ENVWA/2)
- Recommendations to ECE Governments on Economic Instruments for Rational Utilization of Water Resources, 1980 (ECE/ENVWA/2)
- Recommendations to ECE Governments on Rational Utilization of Water, 1979 (ECE/ENVWA/2)
- Recommendations to ECE Governments on Selected Water Problems in Islands and Coastal Areas with Special Regard to Desalination and Ground Water, 1978 (ECE/ENVWA/2)
- Recommendations to ECE Governments on Long-term Planning of Water Management, 1976 (ECE/ENVWA/2)*

In recent years, two additional protocols have been developed in the framework of the convention.

In 1999, in London a protocol on water and health to the 1992 Convention on the Protection and Use of Trans-boundary Watercourses and International Lakes was adopted. It was signed by 36 states; 14 states have ratified it, while 16 ratifications are needed for its entry into force.

The objective of this protocol is to promote at all appropriate levels, nationally as well as in trans-boundary and international contexts, the protection of human health and well-being, both individual and collective, within a framework of sustainable development, through improving water management, including the protection of water ecosystems, and through preventing, controlling, and reducing water-related disease.

The parties are obliged to take all appropriate measures to prevent, control, and reduce water-related disease within a framework of integrated water-management systems aimed at sustainable use of water resources, ambient water quality which does not endanger human health, and protection of water ecosystems.

* Convention on the Law of Non-Navigational Uses of International Watercourses.

In taking measures to implement this protocol, the parties shall be guided in particular by the following principles and approaches:

(a) The precautionary principle, by virtue of which action to prevent, control, or reduce water-related disease shall not be postponed on the ground that scientific research has not fully proved a causal link between the factor at which such action is aimed, on the one hand, and the potential contribution of that factor to the prevalence of water-related disease and/or trans-boundary impacts, on the other hand.
(b) The polluter-pays principle, by virtue of which costs of pollution prevention, control, and reduction shall be borne by the polluter.
(c) States have, in accordance with the Charter of the United Nations and the principles of international law, the sovereign right to exploit their own resources pursuant to their own environmental and developmental policies, and the responsibility to ensure that activities within their jurisdiction or control do not cause damage to the environment of other states or of areas beyond the limits of national jurisdiction.
(d) Water resources shall be managed so that the needs of the present generation are met without compromising the ability of future generations to meet their own needs.
(e) Preventive action should be taken to avoid outbreaks and incidents of water-related disease and to protect water resources used as sources of drinking water because such action addresses the harm more efficiently and can be more cost-effective than remedial action.
(f) Action to manage water resources should be taken at the lowest appropriate administrative level.
(g) Water has social, economic, and environmental values and should therefore be managed so as to realize the most acceptable and sustainable combination of those values.
(h) Efficient use of water should be promoted through economic instruments and awareness building.
(i) Access to information and public participation in decision-making concerning water and health are needed, inter alia, in order to enhance the quality and the implementation of the decisions, to build public awareness of issues, to give the public the opportunity to express its concerns, and to enable public authorities to take due account.

29.2.7.2.3 Soil Management

29.2.7.2.3.1 European Soil Charter (1972) The European Soil Charter was adopted by the Council of Europe by Resolution (72) 19 of May 30, 1972. A set of annotated principles was spelled out:

- Soil is one of humanity's most precious assets. It allows plants, animals, and men to live on the Earth's surface.
- Soil is a limited resource, which is easily destroyed.
- Industrial society uses land for every culture as well as for industrial and other purposes. A regional planning policy must be conceived in terms of the properties of the soil and the needs of today's and tomorrow's society.
- Farmers and foresters must apply methods that preserve the quality of the soil.
- Soil must be protected against erosion.
- Soil must be protected against pollution.
- Urban development must be planned so that it causes as little damage as possible to adjoining areas.
- In civil engineering projects, the effects on adjacent land must be assessed during planning, so that adequate protective measures can be considered in the cost.
- An inventory of soil resources is indispensable.

- Further research and interdisciplinary collaboration are required to ensure wise use and conservation of the soil.
- Soil conservation must be taught at all levels and be kept to an ever-increasing extent in the public eye.
- Governments and those in authority must purposefully plan and administer soil resources.*

29.2.7.2.3.2 FAO World Soil Charter (1981) The Food and Agriculture Organization (FAO) World Soil Charter was adopted by FAO Conference Resolution 8/81 of 25 November 1981. It consists of principles and guidelines for action that, because of their universal importance, are reproduced in full text.

Principles of the World Soil Charter include

- The use of land resources, comprising soil, water, and associated plants and animals should not cause their degradation or destruction because man's existence depends on their continued productivity.
- It is imperative to give high priority to promoting optimum land use, to maintaining and improving soil productivity, and to conserving soil resources.
- Soil degradation directly affects agriculture and forestry by diminishing yields and upsetting water regimes, but other sectors of the economy and the environments as a whole, including industry and commerce, are often seriously affected as well.
- It is a major responsibility of governments that land use programs include measures toward the best possible use of the land, ensuring long-term maintenance and improvement of its productivity, and avoiding losses of productive soil.
- The provision of proper incentives at farm level and a sound technical, institutional, and legal framework are basic conditions to achieve good land use.
- Decisions about the use and management of land and its resources should favor the long-term advantage rather than the short-term expedience that may lead to exploitation, degradation, and possible destruction of soil resources.
- Land conservation measures should be included in land development at the planning stage and the costs included in development planning budgets.

Guidelines for action to be taken by government include

- Develop a policy for wise land use according to land suitability for different types of utilization and the needs of the country.
- Develop an institutional framework for monitoring and supervising soil management and soil conservation, and for coordinating between organizations involved in the use of the countries' land resources in order to ensure the most rational choice among possible alternatives.
- Disseminate as widely as possible information and knowledge about soil erosion and methods of controlling it both at the farm level and at the scale of entire watersheds, stressing the importance of soil resources for the benefit of people and development.
- Establish links between local government administration and land users for the implementation of the soils policy and emphasize the need to put proven soil conservation techniques into practice, and to integrate appropriate measures in forestry and agriculture for the protection of the environment.
- Strive to create socioeconomic and institutional conditions favorable to rational land resource management and conservation, including provision of security of land tenure and adequate financial incentives (e.g., subsidies, taxation relief, credit) to the land user.*

* Convention on the Law of Non-Navigational Uses of International Watercourses.

29.2.7.2.3.3 UNEP World Soils Policy UNEP's World Soils Policy was adopted at the 12th Governing Council of UNEP in May 1982. It recognized the importance of soil resources and is intended to bring to the attention of the world the extent of world soil degradation and its seriousness. It attempts to encourage and assist countries in improving the productivity and management of their soils and reducing soil degradation. Lists of actions to be taken by international organizations and all national governments are included.*

29.2.7.2.3.4 UNEP's Strategy on Land Use Management and Soil Conservation In 2004, UNEP published its Strategy on Land Use Management and Soil Conservation.

Its objectives are stated as follows:

> The loss and degradation of land resources need to be seen in the context of policy, socioeconomic conditions, and the environment. The impact on agriculture and food production, as well as on the ecological and protective functions of natural and managed ecosystems, is, however, universally recognized. Recently, the United Nations Millennium Declaration, the United Nations Millennium Development Goals, and the World Summit for Sustainable Development (WSSD) Plan of Implementation recognized the maintained integrity and restoration of land resources as a critical factor in achieving economic and ecological sustainability. To meet these challenges, new and innovative approaches are required.*

29.2.7.2.4 Convention on Human Rights and the Environment

Environmental rights do not actually fit into any single category or generation of human rights. However, at the United Nations Conference on the Human Environment held in Stockholm in 1972, the international community declared that "man has the fundamental right to freedom, equality and adequate conditions of life in an environment …a quality that permits a life of dignity and well being, and he bears a solemn responsibility to protect and improve the environment for present and future generations". This might be seen as providing the basis for subsequent elaboration of a human right to environmental quality.†‡

29.2.7.2.4.1 1981 African Charter on Human and People's Rights Among human rights treaties, the 1981 African Charter on Human and People's rights proclaims environmental rights in broadly qualitative terms. The Article 24 of the Charter imposes an obligation on the state to take reasonable measures to prevent pollution and ecological degradation, to promote conservation, and to secure ecologically sustainable development and use of natural resources. The commission's fund order calls for comprehensive clean up of lands and rivers damaged by oil operations, the preparation of environmental and social impact assessment and provision of information on health and environmental risks and meaningful access to regulatory and decision making bodies.§

The 1998 Aarhus Convention on Access to Information, Public Participation, and Decision-making and Access to Justice on Environmental Matters states: "Adequate protection of the environment is essential to human well being and the enjoyment of basic human rights including the right to life itself." It also asserts that "every person has the right to live in an environment adequate to his or her health and well being and the duty, both individually and in association with others to protect and improve the environment for the benefit of present and future generations." Environmental rights are already entrenched in European human rights law as well as in the African charter and the inter-American convention.

29.2.7.2.5 Convention on Biological Diversity

The CBD takes the form of a modern framework agreement in: (1) a substantive meaning, as it stipulates, for the most part, overall goals and broadly phrased obligations, which leave large room for parties on

* Convention on the Law of Non-Navigational Uses of International Watercourses.

† ECOSOC, *Human Rights and the Environment* Final Report (1994), UN Doc.E/CN.4/Sub2/1994/9, p. 59.

‡ Boyle and Anderson (eds.), *Human Rights Approaches to Environmental Protection*, Chapter 3.

§ African Charter on Human and Peoples Rights 1981 Art 22.

how to implement the CBD and achieve its goals; and (2) a procedural sense, as it provides for the adoption of protocols and annexes as may be considered necessary in the light of new scientific evidence and technological developments. The preamble declares that biological diversity should be conserved for both ecocentric and anthropocentric reasons. The former include the role of biodiversity in the continuation of evolution and the maintenance of the life-supporting systems of the biosphere. The latter comprise its genetic, social, economic, scientific, educational, cultural, recreational, and aesthetic values.

By recognizing conservation of biodiversity as a "common concern to humankind," the CBD justifies international obligations being placed on states without the need of another international aspect. Thus, although weaker than the concept of common heritage of mankind found in the 1972 WHC and in Part XI of the 1982 United Nations Convention on the Law of the Sea (UNCLOS), this recognition serves as an important conceptual basis and rationale for the obligations to which the parties have agreed on as imposing restrictions of their national sovereignty.

The opposing views of developing and developed countries on many aspects in the negotiations meant that in many cases a compromise acceptable to all sides had to be found. As a result, many of the CBD's provisions contain clauses such as "as far as possible and as appropriate," "in accordance with its particular conditions and capabilities," and "subject to national legislation," which weaken the obligations to some extent and leave more flexibility for the parties in their implementation of the provisions. Another expression of this compromise could be seen in the inclusion of access and benefit sharing (ABS) as well as the provisions on the financial mechanism.

29.2.7.2.5.1 Objectives of the Convention on Biological Diversity The three objectives of the CBD as stated in its Article 1 are

- The conservation of biological diversity
- The sustainable use of its components
- The fair and equitable sharing of the benefits arising out of the utilization of genetic resources

These objectives reflect the goal to create an international convention that would go beyond conservation measures in the strict sense, and also encompass the broad range of uses of biological diversity and their social and economic dimensions.

Conservation of biological diversity—as defined in Article 2—includes in situ as well as ex situ conservation measures, while the CBD places primary importance on conservation in situ.

The concept of sustainable use is further explained in Part IV.C as a cross-cutting theme to a number of international environmental instruments. The CBD, however, was the first global and binding instrument that included sustainable use of the components of biodiversity (i.e., sustainable use of biological resources of any kind) as one of its main objectives, and provided a definition. According to *Article 2 of the CBD*, "sustainable use" means "the use of components of biological diversity in a way and at a rate that does not lead to the long-term decline of biological diversity, thereby maintaining its potential to meet the needs and aspirations of present and future generations."

The third objective of the CBD is the fair and equitable sharing of the benefits arising out of the utilization of genetic resources, which includes "appropriate access to genetic resources" and "appropriate transfer of relevant technologies, taking into account all rights over those resources and to technologies, and by appropriate funding" (Article 1 CBD). The two sides of this objective—access to genetic resources and the sharing of the benefits arising from their use—are referred to as "access and benefit sharing," or ABS. The obligations relating to ABS are mainly spelt out in *Article 15 CBD*, while other provisions are also relevant.

29.2.7.2.5.2 Principles National sovereignty over natural resources; obligation not to cause significant harm to the environment.

The main principle and starting point for the CBD is the sovereign right of each state to exploit its natural resources pursuant to its own environmental policies. This right builds on the fundamental international legal principle of territorial sovereignty. *Article 3 CBD* confirms *Principle 21 of the 1972*

Stockholm Declaration and connects this right—repeating literally the language of *Principle 21 of the Stockholm Declaration*—to the responsibility: to ensure that activities within their jurisdiction or control do not cause damage to the environment of other states or of areas beyond the limits of national jurisdiction.

In addition to this general restriction by the obligation not to cause significant harm, the CBD restricts this broadly phrased right by setting out a number of obligations on conservation and sustainable use of the parties' biological diversity.

29.2.7.2.5.3 Precautionary Principle and Principle of Prevention Both, the precautionary principle (or precautionary approach) and the principle of prevention are reflected in the preamble, however, not as part of a binding obligation of the CBD. Nonetheless, these preambular clauses can be of importance when interpreting legally binding provisions of the CBD.

With respect to the precautionary principle, paragraph 9 of the preamble states that

> where there is a threat of significant reduction or loss of biological diversity, lack of full scientific certainty should not be used as a reason of postponing measures to avoid or minimize such a threat.

Regarding the *principle of prevention,* paragraph 8 of the preamble notes that

> it is vital to anticipate, prevent and attack the causes of significant reduction or loss of biological diversity at source.

29.2.7.2.5.4 Scope and International Cooperation With respect to the scope of the CBD, Article 4 confirms, in essence, that the traditional rules of public international law apply to the subject matter of the CBD. In relation to each contracting party, the CBD's obligations apply:

a. In the case of components of biological diversity, in areas within the limits of its national jurisdiction
b. In the case of processes and activities, regardless of where their effects occur, carried out under its jurisdiction or control, within the area of its national jurisdiction, or beyond the limits of national jurisdiction

In areas beyond national jurisdiction (ABNJ) (i.e., beyond the national jurisdiction of any state) such as the high seas, Article 5 CBD obliges the parties to cooperate "as far as possible and as appropriate." They can cooperate directly or through competent international organizations. The same applies for "other matters of mutual interest."

This is highly relevant with respect to biological diversity in the high seas. Under Article 5 CBD, parties could agree on concrete measures under the CBD to find international solutions to the problems related to living marine resources as well as to genetic resources in the deep seabed. However, there are also other competent forums and instruments for potential regulation on these subjects such as the 1982 UNCLOS, as recognized by the eight COP (COP-8) to the CBD in Decision VIII/21.

With regard to marine protected areas (MPAs) in the ABNJ, the CBD COP has recently taken a more active role. At the ninth COP (COP-9), for example, the parties adopted scientific criteria for identifying ecologically or biologically significant marine areas in need of protection, as well as the scientific guidance for selecting areas to establish a representative network of marine protected areas. But generally, parties have, so far, been somewhat hesitant to go much further under the CBD.

29.2.7.2.5.5 Main Obligations

Conservation of biological diversity: Conservation of biological diversity is the main aim of the CBD. Accordingly, the range of obligations of the parties relating to the first objective is broad.

National biodiversity strategies and action plans and integration of biodiversity concerns into plans, programs, and policies.

Articles 6 and 7 spell out general measures relating to both conservation and sustainable use of biological diversity.

Article 6 CBD requires each party "in accordance with its particular conditions and capabilities" to

a. Develop national strategies, plans, or programs for the conservation and sustainable use of biological diversity
b. Integrate the conservation and sustainable use of biological diversity into relevant sectoral or cross-sectoral plans, programs, and policies

The central planning instruments referred to in Article 6 (a) are the so-called national biodiversity strategies and action plans (NBSAPs), which every country is supposed to develop: (1) to reflect how it is going to fulfill the objectives and obligations of the CBD in light of the specific national circumstances (strategy); and (2) to plan the related sequence of steps to be taken in order to meet the goals (action plan). Most countries have developed their NBSAP (some have already revised it once or even twice) and have entered the more challenging phase of implementing them.

The COP has, on several occasions, provided guidance or endorsed guidance developed by other organizations for the preparation and implementation of the NBSAPs. The revision of the implementation of the NBSAPs is closely linked to the obligation of parties to report on measures that have been taken for the implementation of the provisions of the CBD and their effectiveness in meeting the objectives of the CBD (Article 26 CBD: national reports).

The obligation of Article 6 (b) to integrate consideration of the conservation and sustainable use of biological resources into national decision-making is a consequence of the recognition that governmental policies of almost any sector (agriculture, transport, construction, tourism, etc.) may have a significant effect on biological diversity. Therefore, it is not sufficient to leave the task to environment ministries and nature conservation agencies alone. The obligation—which is repeated in general terms in Article 10 (a) CBD—aims at mainstreaming biodiversity concerns across all sectors of the national economy and policy-making framework. It is also interlinked with the CBD's provisions on environmental impact assessments (EIAs). The CBD Secretariat calls this integration and mainstreaming the "complex challenges at the heart of the convention."

29.2.7.2.5.6 Identification and Monitoring For proper decision-making that takes biodiversity concerns into account, it is essential to increase the data, knowledge, and understanding of biological diversity, its vulnerability and the impact that activities might have on it. This knowledge should also be available and actually used.

Article 7, therefore, contains a set of obligations for identification and monitoring that provides the basis for the fulfillment of a number of other obligations of the CBD, such as Articles *6,8,9, and 10*. The provisions are also linked to Article 12 on scientific research.

As far as possible and as appropriate, parties must:

- Identify the components of biodiversity that are important for its conservation and sustainable use, having regard to the indicative list of categories set down in Annex 1
- Monitor the components thus identified, paying particular attention to those requiring urgent conservation measures and to those that offer the greatest potential for sustainable use [10]

29.3 Public Policy and Decision-Making

Policy can be defined as a proposed course of action of a person, group, or government within a given environment providing obstacles and opportunities that the policy was proposed to utilize and overcome in an effort to reach a goal or realize an objective or a purpose. Public policies are those policies developed by government bodies and officials. However, nongovernmental actors and factors may influence policy development. The special characteristics of public policies stem from the fact that they are formulated by the authorities in a political system, namely, the elders, paramount chiefs, executives, legislators, judges, administrators, councilors, monarchs, and the like [8].

Policy has five basic characteristics:

1. Purposive and goal oriented; rather than random or chance behavior.
2. Consists of courses or patterns of action by government officials rather than their separate discrete decisions. For example, a policy includes not only the decision to enact a law on some topics, but also subsequent decisions relating to its implementation and enforcement.
3. Policy is what government is actually doing not what it intends to do. For example, if a legislature enacts a law without its enforcement, it does not translate into a policy until it is monitored, enforced, and the outcome assessed.
4. Policy may be positive or negative in form. It is positive if it involves some form of overt government action to affect a particular problem, negative if it involves a decision by government officials not to take action or do nothing on some matter on which government involvement is sought. Government in other words, can follow a policy of laissez faire or hands-off, either generally or in a particular area. Such inaction, however, will have major consequences for a society or some of its groups.
5. Public policy is based on law and it is authoritative. Unlike policies of private organizations, public policy has an authoritative, potentially legally coercive quality.

29.3.1 Nature of Public Policy

Public policy follows a course of action that includes (1) policy demand, (2) policy decisions, (3) policy statements, (4) policy output, and (5) policy outcomes:

1. Policy demand: These are the demands made upon public officials by other actors, private or official, in the political system for action (positive) or inaction (negative) on some perceived problems. These demands may give rise to public policy. For example, in the case of drought, financial assistance is factored into the drought policy with respect to farmers.
2. Policy decisions: Policy decisions are decisions made by public officials that authorize or give direction and content to public policy actions. These decisions include the enablement to enact statutes, issue executive orders or edict, promulgate administrative rules, or make important judicial interpretations of law.
3. Policy statements: This is the formal expression or articulations of public policy. These include legislative statutes, executive orders, decrees, administrative rules and regulations, court opinions, as well as statements made by public officials indicating the intention and goals of government and what will be done to realize them.Policy statements can, however, be ambiguous. Furthermore, at different levels, branches of units of governments, there might be conflicting policy statements on an issue.
4. Policy output: These are tangible manifestations of public policies. These include the efforts of the government in enforcing and realizing the objectives of a stated policy.
5. Policy outcomes: These are the intended or unintended consequences of action or inaction by the government on a particular issue. It is fairly easy to measure. For example, welfare policy output are fairly easy to measure, such as amount paid as benefits, average level of benefits number of people aided, and the like. However, the outcomes or consequences of these actions are difficult to ascertain, for example, whether welfare benefits have increased personal security and contentment or reduced individual initiatives.

29.3.2 Policy Process

The policy process consists of three stages: (1) policy formulation, (2) policy implementation, (3) policy evaluation.

1. Policy formulation
   Formulation of policy falls within the purview of the policy makers. For the purpose of this chapter, the policy makers are those within the political and administrative sectors of government. The political system of a country contributes largely in the way policy is formulated. In most instances, the political executives and parliament are principal actors. Career officials in government play a significant role in policy formulation irrespective of the political system of a country.

   In the Western system of democracy, all the three arms of government, namely, legislature, judiciary, and executive, play significant roles in policy-making. The American judiciary in general and the Supreme Court in particular are widely acknowledged as making significant inputs into policy formulation.

   There are four distinct steps in policy formulation: (1) problem identification, (2) development of alternatives, (3) analysis of alternatives, and (4) selection of one alternative. In respect of the second and third steps, a range of techniques and tools has been developed over the past three decades to assist the policy maker. A group of these techniques termed operational research include statistical, mathematical, and computer modeling such as linear programming, game theory, probability theory, and network analysis. In assessing and ranking of choices, the techniques that have been developed include cost-effectiveness analysis, cost–benefit analysis, opportunity cost, and the construction and use of models. Cost-effective analysis helps to determine which alternative is the most efficient for achieving a given objective, while cost–benefit analysis helps to determine whether an efficient alternative is in fact worth the cost. The idea of opportunity cost refers to the cost of what will be given up choosing a given alternative. For example, during a drought episode, water rationing has to prioritize whether to give adequate water to human beings to the detriment of endangered fish species. Of these techniques, the most widely used is cost–benefit analysis (CBA). However, the constraint with CBA is the difficulty of measuring precisely the cost and benefits of public goods and services.
2. Policy implementation
   The implementation of policies refers to the activities that are carried out in the light of established policies. For an effective policy implementation, the following conditions are desirable:
   - Policy to be implemented should be clear and specific.
   - The implementing organization should be named.
   - The target group to be affected by the new policy should be specific.
   - The environment within which the entire implementation process takes place should be clearly stated.

   There can be challenges in the implementation of policy if the formulation stage is defective in consultation and techniques; in many instances, the target group gets to know a policy at the implementation stage, thus causing modification or total abandonment. Therefore, activities carried out at the formulation stage have an impact on the success or failure of implementation.
3. Policy evaluation
   In the policy evaluation process three sets of activities are easily identified: (1) measuring outputs (performance measurement), (2) comparing output performance against the desired results, (3) correcting any deviations or inadequacies. A policy can be evaluated by any of the following: the policy makers, those charged with implementation, members of the public affected by the policy, and external experts or consultants. The overall emphasis on policy evaluation is efficiency and effectiveness. Because policy evaluation seeks to relate a policy objective to a policy program or project, the following evaluation techniques are commonly utilized:
   - Management by objectives (MBO)
   - Planning programming and Budgetary System (PPBS)
   - Zero-based budgeting (ZBB)

Given the role of the legislative in the budgetary process, certain legislative activities can be described as contributing to policy evaluation and these include legislative hearings and investigations. Generally, evaluation exercises must not be limited to quantifiable costs and benefits but the unquantifiable and intangible benefits should also be taken into account. The significance of evaluation lies in the fact that it draws attention to critical factors that help to determine the citizens' attitude to the conduct of government administration [10].

29.3.3 Types of Public Policies

There are different types of public policies and they have specific and sometimes overlapping characteristics. They include the following:

1. Distributive: Distributive public policy promotes private activities that are desirable to a society as a whole. These policies are targeted to provide tangible benefits. There appear to be only winners in this process. There is very little visibility or public attention. These activities include grants for educational research, building airports and roads, and grants for universities. Distributive policies embody the idea of politicians wanting to send some of the funds to their home states or district.
2. Competitive regulatory: Competitive regulatory policies are aimed at limiting the provision of specific goods and services to only a few of several competing distributors. There will be winners and losers but the winners will be regulated. These policies include granting licenses to airlines, television and radio stations, cable television, companies, and electric power producers and other utility operations. Decisions are relegated to bureaucracies, commissions, and the courts.
3. Protective regulatory: The purpose of these policies is to protect the public by setting conditions under which private activities may be concluded. Conditions that are believed to be damaging are forbidden, activities that are beneficial are required. These policies require that a sector of society conform to the general law. It involves a highly political process including special interest groups and lobbying efforts. Examples include high taxation, advertising practices such as alcohol and tobacco, unfair business practices and other protective regulations that protect the public visibility to the public is moderate. Congress and state legislatures make these decisions.
4. Redistributive: Redistributive policies are intended to manipulate the allocation of wealth and property rights. Visibility is very high and congress and courts make the decisions. The decisions are highly political, ideological, and controversial. The goal is to increase equity in society. When redistributive policies are made, the players tend to be labeled liberals or conservatives. Examples include food stamps, affirmative action programs, welfare benefits, civil rights, and health insurance.
5. Structural: Structural public policies involve the nation's foreign policy. These policies involve procuring, deploying, and organizing military resources defense procurements, placement or closing of military bases, and expansion or contraction of the military. The decisions are made in accordance with the formal legislative process by congress. The visibility of these policies to the general public is low.
6. Strategic: Strategic policies assert and implement the basic foreign policy of the nation. Bargaining and debate occur after the policies have been implemented. The president and federal agencies make decisions in this instance. Examples include sale of armaments and grain, the mix of military forces (ratio of ground-based missiles to submarine-based missiles or tariffs imposed on certain countries. These policies have low visibility to the general public until they are made public; then they may become extremely controversial.
7. Crisis: Crisis policies involve short-term responses to immediate threats to national security; visibility for the general public is typically low. The president and his advisors make such decisions. Examples include the crash of a Chinese jet fighter that bumped into an American spy plane off the coast of China in 2001, the Cuban Missile crisis in the early 1960, and the Iranian seizure of U.S. hostages in 1979 taken from the U.S. Embassy.

29.3.4 Decision-Making

Decision-making involves the choice of an alternative from among a series of competing alternatives. Theories of decision-making are concerned with how such choices are made. Rarely will a policy be synonymous with a single decision. It is not uncommon to mix up policy-making with decision-making. Three main theories of decision-making are commonly the reference point and they include (1) the rational-comprehensive theory, (2) the incremental theory, and (3) the mixed-scanning theory:

1. The rational-comprehensive theory
   This is perhaps the best-known theory of decision-making and also perhaps the most widely accepted. It usually includes the following elements:
   - The decision-maker is confronted with a given problem that can be separated from other problems or at least considered meaningfully in comparison with them.
   - The goals, values, or objectives that guide the decision-maker are clarified and ranked according to their importance.
   - The various alternatives for dealing with the problem are examined.
   - The consequences (including costs and benefits that accompany the selection of each alternative are investigated).
   - Each alternative and its attendant consequences can be compared with other alternatives.
   - The decision-maker will choose that alternative and its consequences, which maximizes the attainment of his goals, values, or objectives.

   The result of this process is a rational decision, that is, one that most effectively achieves a given end. However, critics of this theory contend that decision-makers are not faced with concrete clearly defined problems; rather, they first of all have to formulate the problems on which they make a decision. Other criticism is the tendency of decision-makers to confuse personal values with those of the public.
2. The incremental theory
   This theory was proposed by the American political scientist Charles Lindblom. The incremental theory of decision-making or incrementalism is a decision theory that not only tries to avoid the many problems of the rational-comprehensive theory but is also more descriptive of the way decisions are made by public officials. The following characteristics of the incremental theory have been identified:
   - Selection of goals or objectives and the empirical analysis of the action needed to attain them are closely intertwined with rather than distinct from one another.
   - The decision-maker considers only some of the alternatives for dealing with a problem and these will differ only incrementally from existing policies.
   - For each alternative, only a limited number of very important consequences are evaluated.
   - The problem confronting the decision-maker is continually refined incrementalism allows for countless ends-means and mean ends adjustments that have the effect of making the problems more manageable.
   - There is no single decision or right solution for a problem. The test of good decision is that various analyses find themselves, directly agreeing on it, without agreeing that the decision is the most appropriate means to an agreed objective.
   - Incremental decision-making is essentially remedial and is geared more to the amelioration of present, concrete social imperfections than to the promotion of future social goals.

   Incrementalism represents decision-making process in pluralist society due to its political expediency. It is easier to reach agreement when the matters in dispute among various groups are only modifications of existing programs rather than policy issues of great magnitude. Since uncertainty with regards to the future consequences of their actions, incremental decisions reduce the risks and costs of uncertainty. This theory is also realistic because it recognizes that decision makers lack the time, intelligence, and other resources needed to engage in comprehensive analysis of all alternative solutions to existing problems. In summation, incrementalism yields though limited but practical and acceptable decisions.

3. Mixed-scanning theory
   This theory was proposed by the sociologist Amintai Elzoni. Mixed-scanning is an approach to decision-making that takes into account both fundamental and incremental decisions and provides for higher order, fundamental policy processes that set basic directions and incremental process that prepare for fundamental decisions and work them out after they have been reached. Mixed-scanning in a way is a compromise approach that combines use of incrementalism and rationalism in different situations. In some instances, incrementalism will be adequate, while in others, a more thorough approach along rational-comprehensive lines will be needed. The mixed-scanning model also seeks to provide an answer to a major weakness of incrementalism, namely its inability to explain radical social innovation and fundamental decisions. The model also accommodates the differing capacities of decision-makers, some of whom could be incrementalists while others are rationalists. Some of the shortcomings of this theory are the poor descriptive, prescriptive, and research values. In addition, the basis for compromise implied in the mixed- scanning strategy is difficult to determine [10].

29.4 Global Perspectives

Drought is a global phenomenon and many nations in response to the international convention on drought and desertification have put in place laws and policies to combat the phenomenon. These will therefore be enumerated.

1. **The United States of America**
   The National Drought Policy Act of 1998 gave rise to the National Drought Policy Commission, which ensured collaboration between government agencies on drought-related issues. The commission composed of 16 members from relevant agencies is headed by the U.S. Secretary of Agriculture. The commission's groundbreaking report "Preparing for Drought in the 21st Century" laid the groundwork for drought early warning in the United States through a series of recommendations to congress. This recommendation also led to the establishment of the National Integrated Information System and the enactment and signing into law *The National Integrated Drought Information System* (*NIDIS*) *Act* in 2006. The NIDIS Act was reauthorized in 2014. The NIDIS implementation plan includes the following:
   - Develop the leadership and network to implement an integrated drought monitoring and forecasting system at federal, state, and local levels.
   - Foster and support a research environment focusing on risk assessment, forecasting, and management.
   - Create an "early warning system" for drought to provide accurate, timely, and integrated information.
   - Develop interactive systems such as the web portal, as part of the early warning system.
   - Provide a framework for public awareness and education about drought.

   The U.S. drought portal: The U.S. drought portal is part of the interactive system to
   - Provide early warning about emerging and anticipated drought
   - Assimilate and quality control data about droughts and models
   - Provide information about risk and impact of droughts to different agencies and stakeholders

- Provide information about droughts for comparison and to understand current conditions
- Explain how to plan for and manage the impact of droughts
- Provide a forum for different stakeholders to discuss drought related issues

Emergency Rules and Regulations: In addition to the *National Drought Policy Act* of 1998 and the *National Integrated Drought Informative System* (*NIDIS*) *Act* of 2006, states and organs of government can make emergency rules and regulations. For example, The State Water Resources Control Board of California voted to approve any unprecedented across-the-board emergency regulations put in place that will levy fines for wasteful behavior in response to the 3-year-old Californian drought of 2015. Activities like using a hose to wash a car without a shut-off nozzle or using drinkable water in certain decorative water features was banned, while infractions carry fines up to $500. The temporary regulations, which go into place on August 1, 2015, also prohibit watering outdoor landscapes generously enough to create runoff onto surfaces like sidewalks or roadways, as well as using water to clean residential driveways and walkways. Restrictions were also placed on urban water supplies, limiting outdoor irrigation and requiring progress reports. According to the board, 55% or more of daily water use goes into lawns and landscapes in some areas of the state. After making the rules and regulations, the state office of administrative law has to approve the package of rules before they become enforceable.*

In summary, the U.S. drought law takes into cognizance the people's right in the sense that before the emergency rules, the issue is brought to public debate, which enables public participation. In addition, the NIDIS guarantees access to information. It is also important to mention funding and compensation for farmers as a significant aspect of the *National Drought Policy Act*.†

2. **Australia**

The Australia Drought Policy in the twentieth century focused on attempts to drought-proof agriculture through the expansion of irrigation in 1971, the government policy shifted to recognize drought as a natural disaster, enabling support for those affected to be provided under the joint commonwealth–state natural disaster relief and recovery arrangements. In 1989, drought was removed from these arrangements and a review revealed that previous drought policy was poorly targeted, distorted farm input prices, and worked as a disincentive for farmers to prepare for droughts. The outcome of this review is the *National Drought Policy of 1992*. The objectives of this policy are to

- Encourage primary producers and other sections of rural Australia to adopt self-reliant approaches to managing for climate variability
- Facilitate the maintenance and protection of Australia's agricultural and environmental resource base during periods of climatic stress
- Facilitate the early recovery of agricultural and rural industries consistent with long-term sustainable levels

Under the National Drought Policy, a number of assistance programs were introduced including the Rural Adjustment Scheme that offered grants and interest rate, subsidies and the Drought Relief Payment, which provided income support for farmers within declared Exceptional Circumstances (EC). In 1997, these programs became the EC Interest *Rate Subsidy and the EC Relief Payment*.

The EC as defined in 1999 states that such events must

- Be rare and severe, that it must not have occurred more than once on average in every 20–25 years and must be of a significant scale

* California drought, www.ca.gov/drought.
† U.S. Drought Policy, www.drought.uin.edu/planning/uspolicy/.aspx.

- Result in rare and severe downturn in farm income over a prolonged period of time (that is greater than 12 months)
- Not be predictable or part of a process of structural adjustment

Obviously, the Australia Drought Policy is supported by scientific evidences. The Drought Policy is implemented through the Intergovernmental Agencies on National Drought Program Reform (IGA), which is an agreement between the Australian State and territory governments. The IGA aims to refocus government support to encourage farmers to prepare for drought and to manage their business risks instead of waiting until they are in crisis to offer assistance. In addition, the IGA includes guidance in the provision of in-drought assistance.*

3. **Israel**

Like many other countries, Israel drought policy, although not distinctly thus stated falls under the water resources policy and regulation. The Minister of Energy and Water resources is the cabinet member responsible to the parliament (the Knesset) for the management of water resources, proposing the natural water policy for cabinet approval, and subsequently implementing it as well as for Israel's external water relations. However, some aspects of the management, protection, and allocation of water resources fall into the spheres of other ministries such as Agriculture Environmental Protection, Health, Finance, and Interior. Therefore, policy is developed with the consultations of all the affected ministries. *The 2006 Water Law* culminated in the creation of the water authority, an interagency body overseen by a council composed of senior representatives of the Ministries of Finance, Energy and Water, Environmental Protection, and Interior. The Director of the Authority is a cabinet-appointed civil servant reporting to the Minister of Energy and Water and to the Knesset. His nomination by the cabinet is for a period of 5 years. In addition, there is a water board, which is composed of representatives of the government and the public including producers, suppliers, and consumers, whose consent must be obtained for certain measures to be undertaken.†

4. **New Zealand**

Drought policy is classified under a category of adverse events. The agency of government responsible for determining adverse events is the Ministry of Primary Industries (MPI). MPI classifies adverse events that include natural disasters, severe weather, and biosecurity incursions as either localized, medium, or large-scale events.

The MPI assesses each adverse event based on the

- Options available for farmers to prepare for the events
- Magnitude of the event and the likelihood and scale of physical impact
- Capacity of the community to cope with the economic and social impacts

When an adverse event occurs, MPI consults with

- Regional policy agents
- Rural support trust
- Relevant regional and or district councils
- Local civil defense emergency management groups
- Other governmental agencies

Based on gathered information, the MPI advises the Minister for Primary Industries on the scale of the event and the government will decide what support to provide. An adverse event may be declared a civil defense emergency by a local council. Examples of adverse events include the Canterbury Windstorm of 2013, Lower North Island Floods of 2004, and the National Drought of 2005.‡

* Review of NSW Response to Drought Policy Reforms, www.dpi.nsw.gov.au.
† Aided by the Sea, Israel overcomes an Old Foe; Drought, www.nytimes.com/.../water-revolution-in-israel-overcome.
‡ Drought Policy in New Zealand, www.newzealand.gov.

5. **The United Kingdom**

   The Department for Environment, Food, and Rural Affair (DEFRA) is a ministerial department supported by 34 agencies and public bodies that is responsible for safeguarding the natural environment, supporting food and farming industry, and sustaining a thriving rural economy. The Department (DEFRA) under which drought event falls works in tandem with other private organizations and research institutes to formulate and implement drought-related policies, most of which are water related. All water companies must prepare and maintain a drought plan under the provisions of the *Water Industry Act 1991* as amended by the *Water Act 2003*. These complement the 25-year water resources management plans that water companies have a duty to prepare to show how they will manage their water resources into the future. In these plans, companies show how they will collect, store, and transport water to meet demand in a dry year. They also set out the different actions they can carry out at the different stages of a drought and what restrictions they may implement on their customers.

   The Environment Agency acts as a technical advisor to government and, as such, advises government on the water companies drought plans and publishes technical guidance on preparing drought plans in the *Water Company Drought Plan Guideline* (Environmental Agency, 2).*

6. **South Africa**

   Although South Africa has shown concern with food security and the effects of drought since the foundation in 1980 of the Southern African Development Coordination (SADC), it was not until November 1997 that a high-level drought policy seminar was organized in Botswana in response to the threat of a serious regional drought following a strong *El Nino* phenomenon. The report on this seminar recognized that drought in Southern Africa is a normal and recurring event and it called for long-term action in

   - Investment in soil and water management, such as the improved development and management of fragile catchment areas and river basins including small-scale irrigations
   - Reviewing the appropriateness of current crop production patterns and possibilities in support of more intensified crop diversification policies
   - Redirecting research toward more appropriate farming system
   - Improved rangeland and livestock management
   - Reviewing institutional arrangements and physical infrastructure

   The 1992 drought in South Africa was the stimulus for a large number of nongovernmental organizations and government department to launch the National Consultative Forum on Drought (NCFD) to coordinate a response to drought crisis in the country [3]. Drought is regarded as a disaster and therefore included in a white paper on Disaster Management (GOSA—MPACD 1999) and the ensuring *Disaster Management Act 57*, 2002. Unlike previous policies that focused mainly on relief and recovery efforts, this act highlights the importance of preventing human, economic, and property losses and avoiding environmental degradation. The Act is administered by the Department of Provincial and Local Government. A national drought management strategy was developed by the Department of Agriculture as a component of the Disaster Management Act. It is titled *Drought Management Strategy* [9] (*GOSA DOA, 2003b*). The following priority areas and programs were proposed for addressing drought and drought management:

   - Increased awareness and preparedness by way of a national drought plan
   - Reduction of risk to drought through appropriate research plans
   - Establishment of mitigation plans
   - Recovery and development programs—post drought

* Government of South Africa-Department of Agriculture (GOSA-DOA 2003b) Drought impact mitigation and prevention in the Limpopo River, Basin www.fao.org/3/a-y5744e/y5714eod.htm, last accessed on November 21, 2015 [9].

- Implementation of education, training, and information plans
- Risk management with a strong emphasis on an insurance-based solution that can be applicable to the agriculture sector as a whole [3]

7. **Zimbabwe**

The National Policy on Drought management was formulated in 1998 and approved in 1999 by the Government of Zimbabwe (GOZ—NEPC, 1999). The policy deals with drought preparedness, mitigation, and response. Special emphasis was placed on developing sustainable livelihoods for those populations most at risk to drought-induced shocks. The policy states that these activities should be integrated with other developmental programs and projects and that they should form an integral part of all-distinct – province, and national level development policy and planning processes. The policy among other issues emphasizes long-term drought mitigation measures, sharing of risk between government and farmers, forward planning, preparedness, prevention, mitigation response, recovery, and rehabilitation. Some of the strategies of NPDM include

- Facilitating sustainable management of natural resources
- Encouraging crop production only in these areas that are climatically and topographically and biological viable precautions against soil loss and good land use practices through educational awareness, campaign and research into promotion of drought tolerant food crops
- Ensuring correct stocking rates of domestic livestock and establishment of grazing schemes
- Supporting current policies and programs on reforestation
- Ensuring correct stocking rates of domestic livestock and establishment of grazing schemes
- Supporting current policies and programs on reforestation
- Ensuring and enforcing correct protection and management of water catchment areas, construction of more dams, and sustainable exploitations of underground water
- Accelerating rural industrialization
- Promotion of small-scale enterprises
- Reducing land pressure through resettlement and proper land use practices
- Introducing appropriate water resources management and irrigation development schemes

The policy also highlights the need for intensive research on improving the tolerance of staple food crops to drought and diseases.*

8. **China**

The Chinese drought policy is under the administration of China Meteorological Administration. It combines policy of flooding and drought, the latter being 55% of the laws while the former consists of 27%. Some of the laws include *Water Law 2002, Meteorology Law 2002, Regulation of Drought Control 2009, Regulation of Defense Against Meteorological Disaster, Regulation on the Administration of Weather Modification 2002, National Drought and Flood Plan 2006, National Contingency Plan for Meteorological Disaster 2010, National Climate Change Programme 2007, Soil Moisture Monitoring Program* (*SMM*) *2007, Standard Classification of Drought Severity 2008, and Ordinance on Management of Weather Modification.*

The drought policy was developed with the Assistance of World Meteorological Organization at the WMO, Expert Meeting on the National Drought Policy in Washington, DC, 2011. The policy recognizes the establishment of State Flood Control and Drought Relief Headquarters and State Council Office of Emergency Management. Approach to drought is by Multi-Agency Emergency Management Response coordinated by the China Meteorological Administration with the collaboration of Ministry of Agriculture and Forestry, Ministry of Hydrology, and Ministry of Health.

* Country Profile—Zimbabwe—The United Nations, www.un.org/esa/earthsummit/Zimbabwe-c-htm.

The drought plan includes the following:

- Emergency management
- Rescue and relief
- Recovery
- Warning issuance
- Preparedness
- Monitoring and evaluation

The drought policies in China could be categorized into three groups:

1. General climate change policies
2. Drought relief policies
3. Adaptive policies

The general climate change policies have offered guidance or direction on coping with climate change, which includes drought disaster. The drought relief policy aims to resolve the actual drought hazard or very possible drought risk faced by the people. It is usually implemented by the government directly with the purpose of helping the victim out of disaster. The adaptive policy, on the other hand, aims to improve the ability of local people to cope with drought. In contrast to drought relief policy, it aims to change the rules of behavior and social pattern to improve ability of local people. The 2009 Drought Relief Ordinance defines all levels of the government's responsibilities, asks all local governments to set aside a special budget for drought relief activities and gives equal priority to risk reduction [4].

9. Nigeria

The Nigerian drought policy instrument is titled *National Drought and Desertification Policy.* The main goal of the policy is to reduce or where possible prevent the adverse effects of drought and desertification and halve or even reverse the processes of desertification to the end that people's lives are immensely improved and poverty is reduced. The overall administration of all environmental laws is under the purview of the National Environmental Standards and Regulations Enforcement Agency (NESREA) established by the *NESREA Act 2007*. The Act established NESREA and charged it with the responsibility of protecting and developing the environment in Nigeria, as well as enforcing all environmental laws, regulations, standards, policies, guidelines, and conventions on the environment to which Nigeria is a signatory. The National Drought Policy is however not elaborated. Many associated policy instruments are currently in processing stages. These include National Environmental Management Bill, Climate Charge Agency Bill, and Domestication of the Kyoto Protocol Bill. As an interim measure, NESREA operates the National Environmental (Desertification Control and Drought Mitigation) Regulations S.I. No 13 of 2011. This regulation seeks to provide a pragmatic regulatory framework for sustainable use of all areas already affected by desertification and for the protection of vulnerable land.*

10. Canada

In Canada, drought is linked with climate change and water governance. Because the country operates a federal system, the regional governments are big players in drought policy-making and administration. The government policy on water and drought is such that water is predominantly under provincial jurisdiction, although, several aspects are not, including First Nation's land and international rivers, which are under the jurisdiction of the federal government. Programs in drinking water, flood hazard identification, groundwater, lake water quantity, and surface water quality are handled by the regional government environment and sustainable resource development. This department links with the water council and other entities including irrigation districts and association involved in water. The regional environment department oversees the

* State of the Nigerian Environment, www.unccd-prais.com/4f8e50bb-d10d-450b-8aie/-a0fa014a4a65.

climate change adaptation framework and agriculture department producer adaptation programs in conjunction with the Canadian federal government. In the same fashion, response to drought is coordinated by the regional drought management committee and the agriculture drought risk management plan. The main goal of the Canadian drought policy is preparedness, monitoring, and response. The ministry also provides weekly agriculture moisture situation updates during the growing season and monthly during the winter season as a part of general drought-related programming.

The federal government funds these programs with minor contributions from the regional governments. These programs include assisting producers by stabilizing income, providing insurance for crop loss and preparing land to be drought resilient by building infrastructure. Overall, the Canadian water governance system is characterized as a decentralized, multilevel governance system [11].

11. Argentina

Drought and water resources are interlinked in Argentina. Water resources are under provincial jurisdiction and the heaviest responsibilities for facing drought reside at the provincial level especially in central-western Argentinean dry lands, far from the federal capital. The water agency (Departments General de Irrigacion DGL) formulates and executes the provincial water policies and decentralizes operations in users' organizations called *Inspecciones de Cauce*. At the provincial level, there is an office charged with coping with climate emergencies (the Dirrecion de prevencion de *Contigencias Climaticas*), but it is mainly concerned with agricultural damages from hail. A bill has been proposed to recognize the natural strategic resource of water and to ensure the fundamental right to water and sanitation is guaranteed through *Argentina/S-2362/09 Proyecto de modificacion a la Ley de Gestion Ambiental de Aguas Art 3* [11].

12. Ethiopia

Ethiopia is the oldest independent country in Africa and has a total population of 88 million. For many, Ethiopia's recent history makes the country synonymous with drought, and it is the main major natural hazard faced by the country. There are, however, other disasters such as flooding, forest fires, and tectonic activities including earthquakes, as well as increased vulnerability to the impact of climate change. Traditionally, the majority of efforts on drought have been focused on relief work based on National Policy on Disaster Management and Prevention 1993 (NPDMP). The policy has since been modified with the establishment of a Disaster Risk Management and Food Security Sector (DRMFSS) under the Ministry of Agriculture. The shift in policy contains a greater emphasis on the delegation of powers to the regional and local levels as well as community involvement. In addition, information dissemination on community vulnerability and drought preparedness are included. It should be emphasized that the strategy of policy on disaster management and prevention includes other disasters such as flood, earthquakes, and forest fires. The DRMFSS under the MOA (Ministry of Agriculture) is the institution recognized with enforcement and implementation of policy on drought and other disasters. Within the framework of the NPDPM, a National Disaster Prevention and Preparedness Fund (NDPPF) has been established as an emergency fund that provides resources for carrying out relief measures. The fund is owned at the federal level and is managed by the National Disaster Prevention and Preparedness Fund Administration (NPPPFA). An additional risk-financing mechanism is being established through the Livelihoods, Early Assessment, and Protection (LEAP) index, supported by the World Food Program and the World Bank. The LEAP index is intended to harmonize key components of a risk management framework designed to translate early warning information into early emergency response.

Although there is no specific legal regime established in Ethiopia to manage individuals' hazards, there is, however, a consortium of collaborative agencies to address drought. In addition to the Ministry of Agriculture, the Environment Protection Agency (EPA) of Ethiopia has a Climate

Resilient Green Economy Strategy, Ethiopian National Early Warning System, and Risk Mapping (EWS) established in 1976, prompted by the severe famine of 1973/74 and the Ministry of Water and Energy which manages the regulation of water and water resources in Ethiopia, on the basis of a relatively large volume of legislation and policy documents. *Proclamation 1997/2000* (*Ethiopian Water Resources Management*) provides the overarching legal framework for water regulation in Ethiopia and has given the Ministry of Water and Energy necessary power to manage water on behalf of the Ethiopian people. Part of the overall objectives of the Ethiopian Water Resources Management Policy of 1999 are managing and combating drought as well as other associated slow onset disasters through, inter-alia efficient allocation, redistribution, transfer, storage and efficient use of water resources and combating and regulating floods through sustainable mitigation, prevention rehabilitation and other practical measures.[*†]

13. **Kenya**

Drought management in Kenya is under the Disaster Risk Reduction (DRR) Program. The major disasters that Kenya faces include drought, floods, landslides, and fires. For example, the 2000 drought emergency affected the central, eastern, Rift values, Coast and North Eastern Provinces with 4.4 million people requiring food and nonfood assistance, while the 2006 drought affected 37 out of 98 districts, leaving a population of 3.5 million people in need of relief. The Drought Risk Reduction Policy is currently being formulated. A draft of National Disaster Management Policy/Strategy for Kenya and Arid and Semi-Arid Lands Development Policy (ASAL) has been formulated and is in final stages toward review/adoption by the National Assembly/Parliament. The policy includes the following:

- Institutional structures for National Disaster Management Policy
- Coordination for disaster/drought risk reduction initiatives
- Institutional framework for drought management
- Human resources capacities
- Legal framework for disease/drought risk reduction and management
- Liaising with UN/ISDR and other agencies in promoting disaster risk management culture in all sectors and cross-border collaboration
- Peace building and conflict management
- Setting strategies for enhancing communities' resilience to drought
- Setting drought preparedness and contingency planning mechanisms
- Balancing short-term emergency response and short-term development program[‡]

14. **Germany**

Drought management strategy is under climate change impacts on water systems. By implication, the two extremes of climate change impacts, namely drought and floods are taken into consideration: seasonal drought risks in eastern Germany with potential impacts on agriculture and forestry and flooding risks in some river catchments such as Rhine, Danube, Elbe, and Oder. Key policy documents include

1. Federal Water Resources Act, as amended 2012, implemented and enforced by the federal government
2. German strategy for adaptation to climate change (DAS) 2008—Federal Ministry of Environment, Nature, Conservation, and Nuclear Safety (BMU)
   a. Adaptation Action Plan of the German Strategy for Adaptation to Climate Change 2011—(BMU)

[*] Article 39, Proclamation 1/1995 (Constitution of the Federal Democratic Republic of Ethiopia).

[†] Article 25, Proclamation 197/20. Part of the overall objectives of the Ethiopian Water Resources Management Policy of 1999.

[‡] Drought Policy Kenya, www.kenya.gov.

b. Climate change in Germany—Vulnerability and Adaptation of Climate Sensitive sections 2005—Federal Environmental Agency
c. Lãnder Adaptation Strategies Individual cities and local authorities—draft proposal of individual Lãnders individual cities and local authorities
d. Federal Water Resources Act, entered into force 2010
e. Ordinance for the Protection of Surface Wales 2011
f. Waste Water Charges Act, as amended 2005
g. Drinking Water Ordinance 2011

Part of the challenge to drought and disaster policy implementation in Germany is the fact that a daily national insurance for natural hazards does not exist. However, there are awareness-raising campaigns on Lãnder level with the goal to raise the percentage of people and enterprises with voluntary insurances against natural hazards. There is a recent incorporation of funding scheme to promote adaptation to climate change at the level of individual enterprises and local authorities [6].

15. **Iran**

The Iranian policy on drought is based on the UN Convention on Drought and Desertification and efforts have been made to domesticate the law in addition to nomination of the UNCCD National Focal Point. Some of the policy strategies include

- Promotion of civil institutions and NGOs network for National Action Plan
- Revision of the macro-structure of agriculture and natural resources management through organizational integration
- Establishment of a High Council for the Environment
- Establishment of three scientific and research centers (International Centre for Co-existence with Desert and Desert Research Centres in Tehran and Yazd provinces)
- Expansion of agriculture and natural resources training and research institutes with emphasis in management in arid and semiarid regions
- Formulation of a million hectares of antidesertification plan
- Adopting criteria and indicators of desertification in Iran
- Participation of all stakeholders to observe the World Day to Combat Desertification aimed to institutionalize antidesertification culture and activities
- Recharging water tables to an annual volume of 1.4 billion m^3*

16. **India**

There is no separate policy on drought but part of National Policy on Disaster Management and National Disaster Management Guidelines 2010. However, the India drought policy is based on culture of preparedness, mitigation, and response-implementing institutions including the Ministry of Agriculture, meteorological field units, The Central water Commission, National Remote Sensing Centre, and National Rain-Fed Area Authority. As part of the strategy, some of the actions include

- Issuance of weekly crop advisories
- Indices used for drought monitoring
- Using Standard Precipitation Index (SPI) to monitor drought on monthly basis
- Vulnerability assessment

In addition, the National Agricultural Drought Assessment and Monitoring System (NADAMS) project provides near real-time information on prevalence, severity level, and persistence of agricultural drought at state, district, and subdistrict levels. Further, a drought atlas for India is being developed by the National Atlas and Thematic Mapping Organization (NATMO). Other drought-policy-related programs include The Green India Mission, Integrated Watershed Management

* Iran—UNCCD, www.unccd.int/Acti.

program, Mission for Sustainable Agriculture, The Mahatma Gandhi National Rural Employment Guarantee Scheme, Food Security Mission, and National Mission on Micro-Irrigation.

- Capacity building through participation in International training courses
- Organizing international seminars to discuss New Technologies in combating desertification and drought*

17. Russia

The Russian drought policy revolves around the agricultural adaptation policies based on two documents:

1. Climate Doctrine of the Russian Federation 2009
2. Implementation Plan of the Climate Doctrine adopted in 2011

The doctrine recognizes the impact of climate change and extreme weather events on different sectors of Russia's economy including agriculture and sets out a general framework for adaptation and mitigation policies. The implementation plan outlines key activities, responsible executive authorities, and implementation for those activities. Two main activities listed in the implementation plan concern adaptation for the agriculture sector and they are

- Mitigation of agricultural disasters is achieved through the development of a method of calculating risks and damages from climate change, and development and implementation of agricultural adaptation measures
- Optimization of operations in the forestry and agricultural sectors, including stimulating activities related to implementation of agricultural adaptation measures†

18. Brazil

Brazil's National Policy to Combat Desertification and Mitigate the Effects of Drought

The Brazilian initiative to combat desertification and mitigation of the effects of drought is underpinned by the law establishing a national policy to combat desertification and mitigate the effects of drought. The definition of desertification in new Brazilian *Law number 13,153*, which entered into force July 31, 2015, and which establishes the *National Policy to Combat Desertification and Mitigate the Effects of Drought*: "Desertification is land degradation in arid, semi-arid, and dry sub-humid areas resulting from various *factors and vectors*, including climatic variations and human activities." The new Brazilian *Law number 13,153* also tells the difference between factors and vectors of desertification. According to this law, *factors of desertification* are the *original natural conditions* that make the most fragile environments susceptible to degradation processes. Otherwise, *vectors of desertification* are forces that act both on society and the environment, **including** *direct human interferences* on them and also *human actions that worsen natural disasters.*

Although the main purpose of the new *Law number 13,153* is to establish mechanisms to combat desertification and mitigate the effects of drought in Brazil, this law also *introduces concepts*, especially that of "*vectors of desertification*," which will very probably be invoked to punish individuals, companies, or other legal entities for environmental damages related to desertification; not only because of *Law number 13,153*, but also because of some other laws already adopted in local, state, and federal governments in Brazil to guarantee sustainable development. For instance, Brazilian *Law number 10.228*, enacted in May 2001, required public officials to identify decertified lands in all national territory and farmers had to draw up environmental management plans and use technology capable of interrupting the degradation processes and recovering the land.

* Drought conditions and management strategies in India, www.moef.gov.in/sites/default/in/india-country%20Report%20-Hanoi.

† The 2012 Drought: Russian farmers and the challenges of adapting to extreme weather events, https://www.oxfarm.org/…/cs-russia-drought-adaptation-270913-3.

UNCCD had also already included "*human activities*" in the concept of desertification. It was ratified by the Brazilian Parliament ("The National Congress") by *Legislative Decree number 28*, enacted in June 1997 and received Presidential Assent in *Decree number 2.741,* enacted in August 1998. Since then, UNCCD was promulgated into Brazilian Law. The Brazilian National Constitution of 1988 indicates in Article 225, under Chapter VI ("Environment") in Title VIII ("The Social Order") that

> "All have the right to an ecologically balanced environment, which is an asset of common use, and essential to a healthy quality of life, and both the Government and the community shall have the duty to defend and preserve it for present and future generations."
>
> And in paragraph 3 of the Article 225, Constitution determines
>
> "Procedures and activities considered as harmful to the environment shall subject the offenders, be they individuals or legal entities, to penal and administrative sanctions, without prejudice to the obligation to repair the damages caused." As a matter of fact, desertification does not refer to the expansion of existing deserts. It is happening in dry-land ecosystems covering about one third of the world's land area. Inappropriate land use or over-exploitation of such extremely vulnerable areas can lead to desertification, in the definition of "desertification" given above, as land degradation in arid, semi-arid, and dry sub-humid areas, characterized by reduction or loss of biodiversity [6] or biological productivity or complexity in agriculture lands. And when human actions violate formalized laws, this turns desertification into an environmental legal problem."

This means environmental compliance is crucial for good achievements, notably in agricultural activities and large projects that currently are or may come to be located or developed in Brazil's desertification-prone areas ("Areas Susceptible to Desertification" is the most used terminology in Brazil). And it is relevant to highlight that the legal concept of "Areas Susceptible to Desertification" includes the vulnerable territories to the desertification processes, obviously, but also their surroundings. Besides, desertification is a social economic problem that affects all levels of society, mainly poor people, as it is very much related to diminishing productivity of the land. This all explains why earlier in the 1992 Rio Earth Summit desertification was mentioned as one of the three greatest challenges to sustainable development, along with climate change and the loss of biodiversity. The "United Nations Convention to Combat Desertification in Those Countries Experiencing Serious Drought and/or Desertification, Particularly in Africa" (UNCCD, already mentioned earlier) came into force in December 1996 (Brazil joined in June 1997), and it is noted that parties to the Convention were:

> "mindful that desertification and drought affect sustainable development through their interrelationships with important social problems such as poverty, poor health and nutrition, lack of food security, and those arising from migration, displacement of persons and demographic dynamics."

The new Brazilian *Law number 13,153* is also about the mitigation of the effects of drought, as stated earlier. So, in Article 3 of *Law number 13,153*, objectives of the National Policy to Combat Desertification and Mitigate the Effects of Drought, have been set to

- Prevent and combat desertification and recover degrading land in all national territory
- Prevent, adapt, and mitigate the effects of drought in all national territory
- Establish mechanisms of protection, preservation, conservation, and recovery of natural resources
- Integrate sustainability into production and use of water resources and also into production and use of water extraction, water storage, and water conduction infrastructure with actions to prevent, adapt, and combat desertification and land degradation

- Stimulate scientific and technological researches
- Explore mechanisms to foment researches and increase knowledge about the process of desertification and about drought events in Brazil, as well as about degraded land recovery
- Promote water, energy, food, and environment security in Areas Susceptible to Desertification
- Promote social environmental education for those involved in combat to desertification
- Coordinate and promote interinstitutional actions with partnership of civil society organizations on the theme
- Foment environmental sustainability of production, including eco-agriculture, silviculture, and agro-forestry systems, with local product diversification and beneficiation
- Improve the conditions of life of the population affected by processes of desertification and drought events
- Support and foment social and environmental sustainable development in Areas Susceptible to Desertification
- Support social and environmental sustainable irrigation systems in lands proper for activities, by taking into consideration processes of salinization, alkalizing, and degradation of soil
- Promote water extraction, water storage and water conduction infrastructure, irrigated agriculture, efficient use and reuse of water in agriculture and forestry in Areas Susceptible to Desertification

Obviously, there has already been in Brazil some initiatives concerning combat to desertification, such as, for example, the National Action Program PAN-Brasil, which was featured in 2004, and those of the National Institute for the Semi-Arid and, also, some others initiatives concerning the mitigation of the effects of drought, like the ones carried out by the Ministry of National Integration. Also, the new law is expected to foment new investments on scientific and technological researches to bring up tools toward sustainable development, from a more optimistic point of view. Lastly, the new law can generate infrastructure contracts and revenue. This new law also allows the Brazilian Federal Administration (Executive Branch) to establish the National Committee for Combating Desertification. *Law number 13,153* not only applies to the Brazilian federal government but also to state and local governments.*

29.5 Discussion

Drought policies are guided by international environmental laws, which are domesticated in various sovereign states. Like most environmental laws, scientific evidences play a crucial role. However, most laws on drought are still evolving from state to state. The underpinnings of most national drought policies are *Agenda 21, Chapter 12; Managing Fragile Ecosystems and Combating Desertification and Drought declared at the 1992 UN Declaration* in environment and development in Rio de Janeiro, the *United Nations Convention to Combat Desertification* (UNCCD) adopted on October 14, 1994, and *Hyogo Framework for Action 2005–2015: Building the Resilience of Nations and Communities to Disasters 2005.* These three can be regarded as direct drought-related or primary international drought laws. Other drought-related laws, which are secondary, are those laws involving protection of ozone layer, climate change, water resources management, and land use management.

The institutional framework for implementation of these laws and policies varies from state to state; however, the common ground is the multiagency approach in the shaping of national drought policy. The very prominent departments and agencies include meteorology, agriculture, disaster management, water resources management, and some states such as China have the department of Health as part of the implementing agencies. It is, however, obvious those drought policies are not well developed in most

* Brazil's National Policy to Combat Desertification and Mitigate the Effects of Drought, Fus.com.br/…/brazil-s-national-policy-to-combat-desertification.

countries, mainly because many of the signatories of the relevant conventions are yet to domesticate them into their national laws.

Of importance is the issue of funding, international cooperation, capacity building as components of most drought policies. This is in particular reference to insurance for farmers, compensation of crop loss, and provision of emergency services. Virtually all national drought policies regard drought incidences as a disaster and adverse events and the provision of many policies accommodates classification of such events. In the same fashion, notification is at different levels of government. The making of drought policy in many instances follows the incremental pattern. There are modifications and sometimes emergency regulations in response to drought. For example, the state of California had to make emergency laws to conserve water in managing the persistent drought of over 3 years in 2015. Excessive usage of water attracted fines of up to $500 in some instances.

The most prominent laws in drought management are water related; the air pollution, climate change, and soil component are quite minimal, although supposedly integrated in the drought management strategies. The human rights aspects of drought policy are somehow neglected in many national policies. The right to water and sanitation, safe and healthy environment, equality, access to information and participation are not clearly stated. However, the U.S. and UK drought policy have strong human rights component in their implementation. These include public participation, access to information, and attempt to reach most vulnerable groups, who are usually farmers in the remote areas. There is need for international cooperation, capacity building, and transfer of knowledge and technology on a global scale for drought to be effectively managed or better still prevented.

The 1994 United Nations Convention to combat desertification in those countries experiencing serious drought and/or desertification, particularly in Africa, requires state parties to adopt an integrated approach addressing the physical, biological, and socioeconomic aspects of the process of desertification and drought (Art 4 (2) (a)). It is therefore expedient that drought laws and policies should take into consideration the environment as a whole, namely, air, water, soil, and biological diversity. More detailed texts calling for integrated pollution prevention and control exist on the regional level, in the European Union and the OECD. The purpose of integrated pollution prevention and control is expressed in an OECD Council recommendation of January 31, 1991, to prevent or minimize the risk of harm to the environment as a whole, recognizing the integrated nature of the environment media (air, water, and soil). Thus, environmental law moves from trying to determine the level of pollution, which a given sector of the environment can assimilate, to techniques that will eliminate or at least reduce the input of pollutants. In drought events, there are sometimes conflicts in environmental laws, for example, in rationing water usage; endangered fish resources and human use can be in competition. The issue then is to what extent human water requirement can be satisfied at the detriment of sustaining the fish biodiversity. There can be said to be conflict between rights to water and environment and the Convention on Biodiversity [2,5].

Drought and water scarcity have resulted in the need for international negotiations, cooperation, and bilateral and multilateral agreements with obligatory texts. In recent times, Sudan and Egypt have demanded negotiation in respect of the dam built by Ethiopia on the River Nile course. In discussions with Ethiopia and Sudan, Egypt has stated it will need more than its allocated share of water under a 1959 agreement with Sudan, which gave 55.5 billion out of 84 billion m^3 of the Nile water. Egypt has demanded an increase in the water supply due to its expanding population and matters of national security. However, Ethiopia opposes Egypt's proposed guarantee rights to the Nile and continues to reject the allocation amounts of the 1959 agreement, to which Ethiopia was not a signatory. For its part, Egypt remains concerned that the Grand Ethiopia Renaissance Dam will reduce the flow of the Nile and decrease the amount of water available for Egyptians. Ethiopian officials have repeatedly assured their neighbors that the dam will not cause water levels to decrease downstream. It should be recalled that the extent of starvation and deaths that accompanied the Ethiopian drought and famine of 1984 was seen as a tragedy that attracted global attention.

29.6 Summary and Conclusions

Drought laws and policies are dynamic and incremental in nature. In many nations, they are not clearly defined and implementation is usually via multiagency programs and is subject to review as events dictate. Like all environmental-related policies, there is need for standardized parameters that can be adapted by states as they deem fit. The need for coordination by dedicated focal points to make the implementation of the policies effective can also not be overemphasized. Furthermore, it is expedient for the global community to take into consideration the requirements of the poor and less developed countries by way of assistance in capacity building, research, and training to develop their drought laws and policy. National, regional, and international conferences on drought are quite essential as these will afford states the opportunities to share experiences and therefore initiate better drought policies and improve on the existing ones.

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30

Emergency Drought Consequence Plan

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Abstract Water scarcity is a natural phenomenon that happens all over the world and could result in serious problems in arid regions. In this chapter, first, basic definitions of drought and its characteristics and impacts on the environment and society are given. It is emphasized that by appropriate drought planning, the damages of droughts can be mitigated and the resiliency of society in facing droughts would increase. Public participation as a key issue in this regard is also discussed. Then, the features of a successful drought response plan and the challenges in its development are discussed. A multistage approach in emergency drought response plan is introduced. In this approach, different drought indices covering different aspects of drought impacts are utilized and thresholds for drought

initiation, development, and termination are proposed. Furthermore, the necessity of drought monitoring in this utilization approach is discussed. Finally, virtual drought exercise as a useful tool in the evaluation and development of drought contingency plans is introduced.

30.1 Introduction

Although people think that drought is a rare event, it is a normal, recurrent feature of any climate, though its characteristics are highly different from one region to another region. Drought is different from aridity, which characterizes regions with low rainfall, because it is a temporary deviation from the normal weather condition. During drought, different components in weather and hydrological systems are affected, resulting in different types of drought, such as meteorological, hydrological, and agricultural droughts.

Drought also affects society due to the interplay between natural water resources and the demand people place on the water supply. Recent droughts all over the world and their economic and environmental consequences and the affected populations' hardships have highlighted the vulnerability of all societies to drought hazard [10]. In recent years, due to the increasing scarcity of water resources all over the world [2], this vulnerability is also increasing.

Therefore, providing an emergency drought response plan is necessary to increase the preparedness of all participants in drought response to deal with drought impacts and to diminish adverse drought impacts. In this chapter, different issues in the development of an emergency drought response, including purpose, necessities, process, scheme, monitoring, and evaluation, are discussed.

30.2 Basic Definitions and Concepts

30.2.1 Nature and Characterization of Drought

Drought occurs in every climate with varying frequency and characteristics. As a basic definition, drought starts from a deficiency of precipitation over a time period. Drought is defined relative to a "normal" condition, referring to a long-term average condition of balance between precipitation and evapotranspiration in a particular area. Drought severity and impacts are also dependent on the timing (i.e., principal season of occurrence, delays in the start of the rainy season, occurrence of rains in relation to principal crop growth stages) and the effectiveness of rains (related to rainfall intensity, duration, and frequency). Climatic conditions such as high temperature, high wind, and low relative humidity, which are often observed during droughts, can significantly intensify drought severity.

In general, droughts are classified into three groups: meteorological, hydrological, and agricultural. When drought is just defined from the point of view of rainfall deficit, it is called meteorological drought. For water consumers, when water supply declines, drought happens. Therefore, hydrological drought is a result of deficit in water resources over a period of time in comparison with the normal condition. For farmers, drought is a condition because of which agricultural production decreases, defined as agricultural drought. Drought damages could be high in regions with high water supply dependencies and cause serious regional impacts [9].

30.2.2 From Natural to Social Dimension of Drought

As drought develops and impacts the environment of a region, it also impacts communities and individuals in different ways. These costly drought impacts come in a variety of forms. Plants and animals (as well as people) depend on water. Drought limits their food and water resources and damages their habitats. In general, environmental losses during a drought are the result of damages to plant and animal species, wildlife habitat, air and water quality, forest and range fires, degradation of landscape quality, loss of biodiversity, and soil erosion. Drought impacts on the environment and wildlife can be temporary, and in some cases, irreversible [16]. Groundwater level can be affected in a drought event, especially in cases of frequent drought periods, if there was not enough water for aquifer recharge.

Wildfire risk considerably increases in drought conditions. Plants and trees wither and die during droughts because of lack of precipitation, increased insect infestations, and diseases (as a result of drought), and become fuel for wildfires. Therefore, longer periods of drought result in increasing frequency and intensity of wildfires, which affect the economy, the environment, and society in many ways.

Examples of economic impacts of drought include monetary and agricultural production losses because of the destruction of crops/wildlife and increased expenditure by farmers and ranchers to feed and water their animals. Economic impacts can be both direct, such as decreases in dairy production, and indirect, such as increases in the price of some services and products. Hydropower production is also affected by drought. Drought happening during tourist seasons, whereby water demand increases due to the influx of tourists, highly affects the tourism industry and leads to economic losses, especially in communities that rely on the industry.

In addition to the economy, drought also affects society. Examples of drought impacts on society include anxiety or depression about economic losses, conflicts between water users, reduced incomes, fewer recreational activities, higher incidents of heat stroke, reduced quality of life, loss of public safety, less hygiene, and even loss of human life.

Many of the economic and environmental impacts of drought include social components, as mentioned in the earlier examples. Population migration can be stimulated by a greater supply of food and water elsewhere. Migration can happen to urban areas within the stressed area or to regions outside the drought area, and even to adjacent countries. Since the migrants often do not return home, they place more pressure on the social infrastructure of the urban areas, leading to increased poverty and social unrest [16].

Therefore, droughts have significant social and economic consequences that should be taken into account besides the natural impacts. If enough attention is not paid to social dimensions of droughts, then this can lead to long-standing social and economic impacts.

30.2.3 Drought as a Disaster

Drought is different from other natural disasters from varying aspects. Drought is a slow-onset natural hazard, and that is why it is referred to as a creeping phenomenon. Considering drought as an accumulated departure of precipitation from the normal condition, this accumulated deficit may happen quickly over a period of time, or it may take months before the appearance of deficiency in streamflows and reduction in reservoir levels, or increasing depth of the groundwater table. Regarding the creeping nature of drought, its effects often appear slowly (i.e., after some weeks or months). Since precipitation deficits usually first appear as soil moisture reduction, agriculture is the first sector that is affected by drought consequences.

There are some characteristics that significantly make drought different from other natural hazards. Due to the creeping nature of drought, it is often difficult to determine when a drought event starts or ends. Furthermore, it is difficult to find a comprehensive measure to determine the drought situation based on it. Some common questions in this regard are as follows:

- Does drought end when precipitation returns to normal condition, and if so, over what period of time does more than normal precipitation should be sustained for drought termination?
- Does the precipitation deficit need to be erased for the drought to end?
- Is it needed to return reservoirs' and groundwater levels to the normal or average condition for drought termination?
- Since drought has considerable socio-economic impacts that last for a long period, should the end of drought be determined by meteorological or climatological factors, or by the diminishing negative impacts on society and the environment?

Another important feature of drought is that there is not a precise and universally accepted definition of it. The variety of available definitions just leads to more confusion about drought existence and severity. This is because definitions of drought are specific to a region, an application, or an impact.

Drought impacts are commonly nonstructural and spread over a larger geographical area than the damages of other natural hazards such as floods, tropical storms, and earthquakes. This characteristic, besides the creeping nature of drought, makes quantification of impacts and drought planning more challenging in comparison with other natural disasters. This characteristic also makes it difficult to develop accurate, reliable, and timely measures of drought severity and impacts (i.e., drought early warning systems) and, consequently, drought preparedness plans. Furthermore, it is difficult to respond to drought consequences in a large spatial area, which is what usually happens in a drought.

30.2.4 Drought Vulnerability and Drought Resiliency

Droughts have both direct and indirect impacts on society and the environment. The direct impacts can be observed, such as water shortages in different sectors and production decreases, but indirect impacts could be much more devastating, even though it is sometimes difficult to measure them. Therefore, communities' vulnerability to drought is complex and depends on both biophysical and socioeconomic characteristics of the region, which in turn determine the capacity in dealing with drought [15]. What is meant by drought vulnerability is the socioeconomic and biophysical characteristics of the region that results in the region's destruction to adverse the effects of drought.

Similar to other climate disasters, society's vulnerability to drought is dependent on factors such as population, technology, policy, social preparedness, land use schemes, water use in different sectors, economic development, and diversity of economic base, and cultural composition, as well as water governance [7,15,21,27]. For example, in sub-Saharan Africa (SSA), about 90% of the region's food and feed is provided by rainfed agriculture [19], and for more than 70% of the population, it is the main source of livelihood [8]. Due to this high dependency on rainfed agriculture, about 60% of SSA is vulnerable to frequent and severe droughts [4]. In Figure 30.1, different aspects that affect a region's vulnerability to drought are illustrated.

The main factors that determine the drought vulnerability extent are as follows:

1. Fragile physical environment, which is characterized by environmental degradation, lack of ecosystem resilience, and history of extreme hydrological events
2. Fragile economy, referring to economic inequalities/disparities and inadequate funding
3. Lack of local institutions, including lack of social resilience, poor social protection, marginalization, and lack of capacity for recoverability
4. Lack of preparedness, where examples are inadequate warning systems, lack of training, and lack of community mobilization

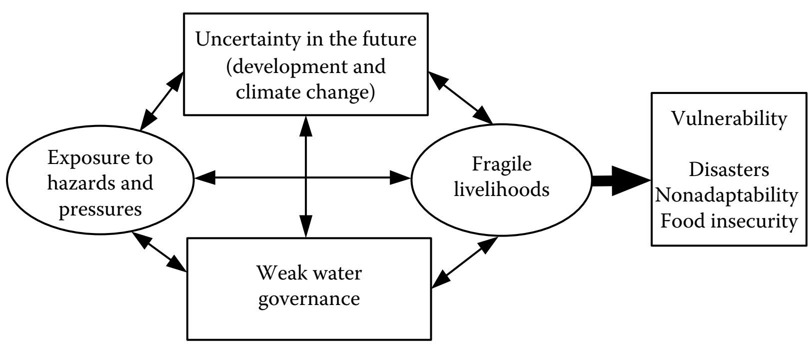

FIGURE 30.1 The vulnerability framework. (Adapted from Pasteur, K., *From Vulnerability to Resilience: A Framework for Analysis and Action to Build Community Resilience*, Practical Action Publishing Ltd, Warwickshire, U.K., 2011.)

Based on [24], in developing countries, three out of four poor people live in rural areas [24]. These areas are characterized by the four aforementioned characteristics of drought vulnerability. The impacts of drought are often intensified in these regions because of unsustainable development. The livelihoods of these people are affected through the loss of assets, loss of food sources, and loss of income. These people may lose all of their properties in order to survive because they have no other choices. This makes their future recovery impossible and they become poorer after each drought. Therefore, increasing societies' resiliency in dealing with droughts is a vital issue.

In general, drought resilience can be defined as the ability of societies to resist, absorb, cope with, and recover from drought impacts and to adapt to long-term changes in a timely and efficient way. Drought-resilient societies, even when affected by significant drought events, are able to recover or adapt their livelihoods and improve their life situation and move out of poverty.

For increasing people's resilience, it is needed to address the factors that underlie their vulnerability, as shown in Figure 30.2.

The diversity and security of people's livelihoods are improved by providing options to live or work in areas less exposed to hazards, or having more resources to draw on in order to cope and recover when they are affected by drought impacts. Increasing the preparedness to deal with drought significantly reduces exposure to it. An improved understanding of future situations and long-term trends, including climate change, helps people to draw on their available resources in appropriate ways to adapt to future changes. Finally, by creating a more enabling governance environment, people will participate in processes of decision-making, service provision, and resource allocation. All of these will increase societies' resilience in coping with severe drought events and decrease the expected damages. Resilient people are able to recover promptly from drought hazards and adapt effectively to long-term trends, and are therefore able to use their resources effectively to step out of poverty, as shown in Figure 30.3. Furthermore, in planning to move from drought vulnerability toward drought resilience, special attention should be paid to bridging the gaps between different planning and managements steps at the local (micro), district or provincial (meso), and national or international (macro) levels [18].

30.2.5 From Crisis Management to Drought Planning

Mitigating the adverse effects of drought does not rely just on the crisis management process but needs an integrated usage of all components of the cycle of disaster management as shown in Figure 30.4. Typically, when a drought event occurs, governments and related agencies start assessment, response, recovery, and reconstruction activities for returning society to a pre-disaster state. This process is called crisis management, and less attention is paid to preparedness and mitigation actions as well as to the development of prediction/early warning systems. The reason is that individuals and agencies consider drought as a rare and random event, and therefore, drought planning practices are not commonly completed before the next event. That is why regions commonly move from one disaster to another with limited risk reduction.

Since drought is a normal part of climate, strategies for reducing its impacts and responding to emergencies should be well defined in advance. Drought planning focuses on risk management for reduction in socioeconomic and environmental impacts, and drought management plans provide important instruments to achieve this. A drought management plan provides a dynamic framework for preparing and effectively responding to drought, including periodic reviews of the achievements and priorities, redefinition of goals, means, and resources, as well as improvement in institutional arrangements, planning, and the decision-making process for drought impacts' mitigation.

These objectives are achieved by providing effective and timely information and developing early warning systems and drought risk maps, as well as by effective networking and coordination among different levels of decision-makers.

Furthermore, including sufficient capacity for contingency planning before drought starts and formulating appropriate policies to reduce vulnerability and increase resilience to drought are necessary.

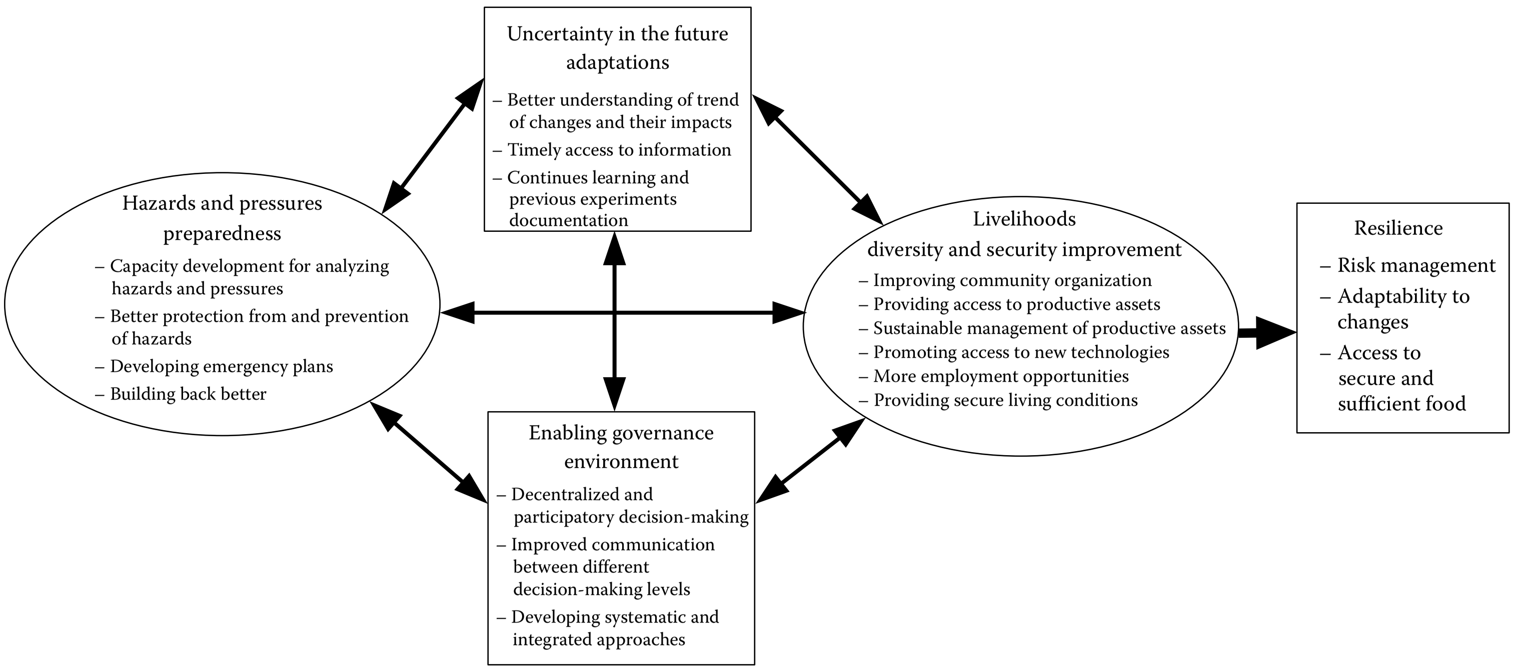

FIGURE 30.2 The drought resilience framework. (Adapted from Pasteur, K., *From Vulnerability to Resilience: A Framework for Analysis and Action to Build Community Resilience*, Practical Action Publishing Ltd, Warwickshire, U.K., 2011.)

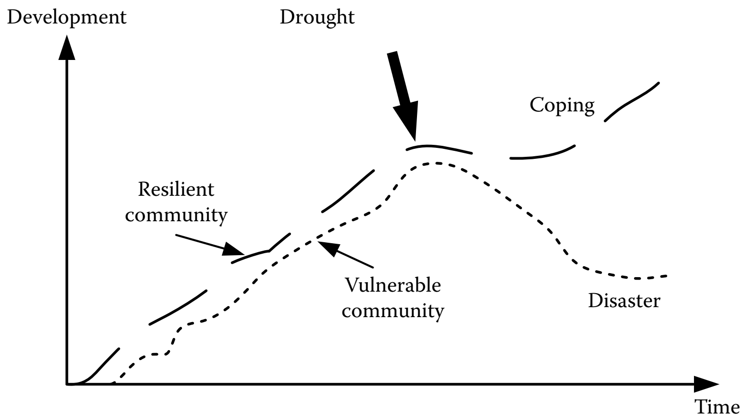

FIGURE 30.3 Resilient and vulnerable communities in dealing with drought.

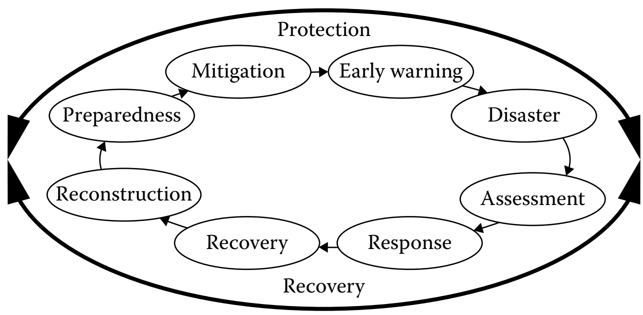

FIGURE 30.4 Cycle of drought disaster management. (Adapted from Drought management: Scientific and technological innovations.)

This can be provided by establishing the institutional capacity to assess drought characteristics in a region, such as frequency, severity, and spread, and their impacts on crops, livestock, the environment, and populations [10].

30.3 Drought Response Plan

Drought response plan is an essential component of regional water resources policy and strategies, especially in drought-prone areas. Drought response plans should be prepared in advance before they are needed, based on careful studies concerning the characteristics of the drought, its effect, and the mitigation measures, with due consideration of the social, political, and economic conditions of the region. This provides time to receive public review and comment about the plan before its application in a crisis mode. Furthermore, drought response plan development before a drought allows selection of optimal responses consistent with the varying severity of shortages.

The purpose of a drought response plan is to provide a management framework for dealing with drought. In addition, it may be used to manage water emergencies that result in temporary loss or reduction in service due to non-climate-related factors.

The drought contingency plan is triggered by reductions in surface water allotment or by the inability to satisfy system water demand for any reason. Most water utilities and communities define different stages (severity) of drought, and appropriate action for each stage. The plan is triggered in stages based on allotment or when demand is projected to exceed supply. Public outreach and education programs should be prepared in advance, with printed materials readily available for distribution.

30.3.1 Purpose of Emergency Drought Response Plan

The main purposes of an emergency drought response plan can be summarized as follows:

- Provision of a continuous, cost-effective, adequate, safe, and reliable supply of high-quality water in emergency conditions of drought, especially for domestic water use, sanitation, and fire protection.
- Identification and application of successful public information strategies, which will motivate the community to participate in demand management practices during drought.
- Definition of different drought stages and providing a programmed response for each stage to effectively reduce water consumption of the available supply and conserve it for the following months during drought, with minimum adverse impacts on the region.
- Protection and preservation of public health, welfare, and safety.
- Minimization of the adverse effects of water shortage in the region.
- Establishment of criteria for declaring different stages of drought emergencies.
- Definition of procedures for continuous evaluation and exercise of the drought response plan and periodic revision of the plan in response to changing characteristics and needs of the region.

In summary, it can be said that a drought response plan aims to determine drought occurrence and severity; prevent sudden and extreme water shortages during drought, especially in domestic usages; provide equitable water supply in the region; minimize drought impacts and increase society's preparedness in dealing with droughts through providing needed information and education.

30.3.2 Drought Response Plan Challenges

Based on the defined purposes for a drought response plan, there are important challenges that an effective drought response plan should overcome. The main challenges, especially in developing countries, are as follows:

1. Selection of an efficient, simple to understand, and representative indicator of drought occurrence. As was mentioned before, there is no unique and integrated drought indicator for drought planning, but a variety of drought indicators, each of which represents a specific aspect of drought. Thus, in the selection of an indicator, site-specific characteristics should be considered.
2. Determination of different drought stages is an important challenge. The definition of drought stages should be in a way that efficient drought management practices can be applied timely to minimize adverse drought impacts and the risk of more severe drought impacts resulting from a worsening of the situation.
3. Absence of an organizational structure and delivery system to ensure information flow between and within levels of government.
4. Absence of documentations on previous drought plan experiences to be used for the identification of the advantages and disadvantages of past drought plans for their incorporation in future drought plans.
5. Lack of appropriate mechanisms for public involvement in drought planning and motivations for their participation in drought plans.

Therefore, a successful and effective drought plan should provide appropriate solutions for these challenges and incorporate them.

30.3.3 Optimal Drought Response Plan Development

Drought emergency response plans should be developed in an optimal way, with the least cost. These optimal plans are identified based on (1) the risk of water shortage (i.e., probability and severity of water supply deficits) for the system under study during the planning period, (2) possibility and costs of emergency water supplies, and (3) the effectiveness and costs of short-term demand management (or water conservation) measures.

Regarding previously mentioned concepts, short-term drought management options are ranked according to their cost-effectiveness in order to facilitate the formulation of staged drought contingency programs. By balancing the incremental cost of long-term drought plans' measures (such as increasing the water resource capacity or permanent modification of demand) with the expected cost of implementing phased drought contingency plans, long- and short-term plans for dealing with droughts are formulated.

A number of short-term measures may be applied to deal with temporary water shortages during different stages of drought. These measures are evaluated based on their effectiveness in demand reduction and improvement of the system's efficiency. Measures that are applicable, technically feasible, and socially acceptable are selected. Finally, the quantity of water saved and the total cost associated with each measure are determined. Similarly, this process is repeated to identify and evaluate possible emergency water supplies. The "best" packages of emergency measures can be defined among the evaluated measures using optimization approaches [3].

30.3.4 Drought Response Plan Responsibilities

There are different levels of responsibilities in drought response plans, including local and governmental authorities. The local entities at basin or province level, working on water supply and related infrastructure as well as those related to public health and environmental protection, are responsible for drought emergency response plans.

In the government, organizations and committees included in drought response plans' development, such as water resources management, public health, and environment protection, are as well responsible for drought response plans and their consequences.

30.3.5 Drought Response Plan Development Process

As droughts are a natural component of climate variability in different regions, it is needed to develop drought preparedness and response plans to deal with these extended periods of water shortage in a timely, systematic manner. An effective plan considers the region's exposure and vulnerability to drought and changes in these characteristics with societal changes.

For a successful drought response plan, the availability of three basic elements is necessary. These elements are (1) a drought early warning system, (2) appropriate drought indicators in correlation with thresholds for different stages of drought, and (3) measures to achieve objectives of each drought stage. Furthermore, transparency and public participation are necessary in the development of drought response plans. The main steps in the development of a drought response plan are as follows:

- Identification of the region's characteristics from different aspects of hydro-climatology, the environment, social and economic situations during droughts, and normal conditions.
- Investigation of the region's experience in response to historical droughts, including their advantages and disadvantages.
- Identification of drought characteristics (severity, frequency, and duration) within the basin.
- Development and implementation of a drought warning system.
- Selection of appropriate indicators and setting their thresholds for different drought stages.

- Planning of measures for preventing and mitigating drought impacts on society and the environment that are linked to indicators systems.
- Development of an organizational structure for drought response plans, including identifying a competent entity, committee, or working group to identify drought impacts, proposing management measures, and evaluating drought extension and measures' effectiveness.
- Update and follow-up of the drought response plan.
- Development of specific plans for public participation.

The degree of development of these steps is highly dependent on the basin characteristics and the provided information as well as on the river basin management plan.

30.3.6 Public Education and Participation

To transmit the planning and mitigation measures considered in a drought response plan, public participation is necessary. It is also important to include public participation during the development of the plan to include different stakeholders' opinions, prior to the final decision-making process. In this way, the conflict between different groups affected by the response plan will be recognized earlier and considered in the response plan. In other words, active public participation will result in achieving optimum sustainable equilibrium, through consideration of social, economic, and environmental aspects, and facilitating the long-term application of the plan by consensus.

Considering educational programs to increase public awareness of short- and long-term water supply issues will ensure that people know how to respond to drought, and thus, drought plans do not lose ground during nondrought periods. There should be attempts to provide useful and effective information for different groups of people (e.g., elementary and secondary education, small business, industry, homeowners, utilities) based on their needs in a practical way. Different activities in this regard, such as developing presentations and educational materials for events such as a water conservation week and community observations of Earth Day, relevant trade shows, and specialized workshops, can be useful.

Voluntary public participation in demand reduction activities during droughts can result in up to 25% saving of water. This is directly dependent on the public's belief that the drought/emergency has happened and on their clear understanding of the actions required for water use reduction. However, it should be noted that voluntary water conservation activities do not continue for more than a few months [1].

30.4 Multistage Approach in Emergency Drought Response Plan

An effective response to drought impacts can be provided through a multistage approach. In this approach, the measures to be applied in response to drought are activated as per the drought situation defined in stages. These stages are determined based on drought indicators. The concepts of this approach are further discussed in this section.

30.4.1 Drought Response Levels

The drought response plan determines the key areas for analysis and action to decrease the community's vulnerability to drought. Even though communities should play a lead in the process of analysis, issues and stakeholders beyond the local level should be included. Furthermore, for achieving drought resiliency, it is needed to bridge the gaps between different planning and management steps at the local (micro), district or provincial (meso), and national or international (macro) levels.

In a drought response plan, the necessary capacity development of community members and institutions for analyzing their situation and improving their resilience is recognized. Because of more knowledge of the community about its own environment and outcomes of previous experiments, a community-driven process will lead to a more effective and realistic analysis, plans, and action than those developed by outsiders.

There are groups in each community that are marginalized or disadvantaged in some way, and their inclusion needs particular attention. These groups are often excluded from participating on the basis of age, race, caste, gender, poverty, religion, or other ethnic grounds. These groups are often highly vulnerable to droughts because of their limited participation in decision-making, which could affect them.

While important analyses and actions take place at the community level, in some cases, changes in organizational policy and practice are necessary to lead to a long-lasting and widespread change. Communities' viewpoints and experiments on drought risk reduction should be fed into upper levels of decision-making, including local, national, and global. Communities should be empowered to make their needs and priorities known.

30.4.2 Overview of Drought Indicators

As mentioned before, there is a variety of drought indicators that are used for measuring drought characteristics from different aspects. The common drought indicators are based on hydrometeorological variables, such as precipitation, streamflows, soil moisture, reservoir storage, and groundwater levels. Several of these indicators can be combined into a single indicator on a quantitative scale to form a drought index which is easier to implement. However, the scientific and operational interpretation of an index causes some difficulties, such as how indicators should be combined and weighted in the index and how, based on the index value, the geophysical and statistical characteristics of drought can be determined [25].

Meteorological drought indicators are defined based on climatological variables such as precipitation, temperature, and evapotranspiration. The most common indices in this group include the deciles [6] and the Standardized Precipitation Index (SPI) [14]. Precipitation is the most common variable used in drought indicators development because it directly measures water supplies, affects the hydrological condition, and can reflect drought impacts over different time periods and sectors. But there are some challenges in meteorological indicators' application, especially those based on precipitation, because of high temporal and spatial variability, and lack of enough data in time and over a region (insufficient observation stations). Evaluation of common indicators' performance has demonstrated the advantage of the SPI and deciles over other indices [13].

For hydrological drought indicators' development, water system variables such as groundwater levels, streamflows, reservoir storage, and snowpack are used. The common hydrological indices include the Surface Water Supply Index (SWSI) [20] and the Palmer Hydrological Drought Index (PHDI) [12]. These indicators reflect that hydrological drought usually develops slowly and continues for a longer time period in comparison with meteorological drought. For example, groundwater is the last component of the hydrological system that is affected by drought and is a more conservative indicator for recovering from drought, but its efficiency is limited because of poor understanding of subsurface conditions and anthropogenic influences. Streamflows can integrate other indicators, such as soil moisture, groundwater, and precipitation, but they are highly sensitive to anthropogenic factors, such as development and diversions.

The agricultural indices are commonly based on soil moisture, and the most common index in this group is the Palmer Drought Severity Index (PDSI) [17]. The PDSI is developed based on a soil moisture balance model, using historical records of precipitation, temperature, and the local available water capacity of the soil [22]. Recently, Karamouz et al. proposed a hybrid drought index (HDI) for evaluation of drought severity based on drought damages through integrating the SPI, SWSI, and PDSI indices [11].

30.4.3 Drought Indicators and Thresholds Definitions

In drought plan development, three types of indicators need to be identified:

1. Indicators to identify and determine drought occurrence: These are natural indicators commonly based on precipitation as the necessary parameter and other hydroclimatic variables such as evapotranspiration and soil moisture to distinguish between natural and emergency situations and determine the possible circumstances.
2. Indicators to measure the impacts of drought on the environment, especially deterioration of water bodies. These indicators are especially used in the program monitoring process.
3. Indicators to illustrate the socioeconomic impacts of prolonged droughts.

The first two types of indicators show the occurrence of prolonged droughts and the associated temporary deterioration of water bodies. The second and third types of indicators are used to determine the appropriate measures for mitigating droughts impacts and recover the quality of water bodies, and to provide a summary of drought impacts. These indicators are also used to inform the water users and the public about drought occurrence, impacts, and drought management results.

Drought indicators' thresholds, or triggers, are used to distinguish a drought level and decide when management actions should start and end. Triggers provide information on the drought level, the spatial scale, the time period, and whether drought conditions are progressing or receding. Drought stages (or phases or levels) are categories of drought determined based on drought severity and extension of drought's impacts.

The following factors should be considered in the selection of appropriate drought indices for a drought response plan:

1. Suitability for drought types of concern: Since drought depends on different factors, a single indicator cannot cover all types of drought. The selected indicators should make sense for the system under planning. For example, the SWSI does not provide any information about soil moisture, and the PDSI is not useful in reservoir operation planning.
2. Data availability and consistency: An indicator's performance is dependent on data availability and quality. Therefore, indicators that are based on data whose analysis is difficult, costly, or unreliable are not appropriate for use. It is better to select indicators that are based on data that are already collected, have their quality controlled, and are consistently reported.
3. Clarity and validity: Indicators and triggers must be clear and easy to understand to make drought decisions based on them. Furthermore, to ensure the selected indicators' performance, they should be tested before a drought and evaluated after a drought.
4. Temporal and spatial sensitivity: Indicators and triggers should reflect both temporal and spatial variability. This is because of climatic variability in different regions and time periods. Therefore, indicator levels that imply drought conditions for one time period or one region could imply wet or normal conditions for another time period or region.
5. Temporal and spatial specificity: A specific temporal and spatial scale of analysis should be determined for indicators and triggers. Indicators are calculated for a specific time period, and triggers are associated with a time period for determining drought levels and responses. For example, SPI-4 (SPI calculated for periods of 4 month) below −2 for three consecutive months can indicate a level 2 drought. Indicators also should define the scale of analysis, based on natural or manmade boundaries.
6. Drought progression and recession: At each level of a drought plan, indicators and triggers should be defined for getting into and out of a drought.
7. Statistical consistency: The selected triggers should be consistent with drought levels and other triggers used in a drought plan. Drought decision-making would be really difficult if indicator scales and trigger values cannot be validly compared and combined.

8. Drought management and impact reduction goals: In some plans, indicators that respond quickly to changes are preferred to take early action to reduce drought impacts. But in other plans, indicators with greater stability and persistence may be preferred to prevent from frequent start and end of drought responses.
9. Explicit combination methods: As mentioned in item (1), drought plans need to often use multiple indicators. Therefore, methods are needed to combine these indicators and determine a final drought level. Both quantitative methods, such as the most severe of the indicators, at least one of the indicators, or a majority of indicators, and qualitative methods, such as convening a drought committee to determine when to implement responses, can be used for this purpose. What is important is to clearly specify the procedure of indicators' combination.
10. Quantitative and qualitative indicators: Commonly used indicators based on quantitative data are preferred, but qualitative indicators can also provide useful information. It should be emphasized that indicators are used to help decision-makers and not to replace them. A human expert applying years of experience and expertise to assess drought conditions is able to consider and synthesize numerous quantitative and qualitative indicators.

30.4.4 Drought Response Measures

Measures that are used in a drought response plan can be categorized into five groups as follows [5]:

1. *Preventative measures*: Preventive or strategic measures are used under the normal status. These measures are commonly used on a watershed scale and belong to the hydrological planning domain. The main objective of these measures is empowering and increasing the response capacity (to meet supply guarantees and environmental requirements) of the structural system in dealing with droughts.
2. *Operational measures*: This group of measures are applied when droughts occur at pre-alert and alert stages. These are typically control and information measures in the pre-alert stage and resource conservation measures in the alert stage. In cases of severe droughts, the water resources status may deteriorate to a level that application of emergency operational measures such as water restrictions may be necessary. These measures and restrictions' application for adaptation to drought situation are ranked based on parameters such as users' water supply priorities, environmental water demands, drought severity and status, etc.
3. *Organizational measures*: These measures include the establishment of knowledgeable agents and an appropriate organization to apply and follow-up the drought response plan, and create effective coordination among administrations and public and private entities involved in drought response, especially entities that are responsible for public water supply.
4. *Follow-up measures*: These measures watch out for the compliance and application of the drought response plan and its effectiveness.
5. *Restoration or exit drought measures*: These measures are applied in the post-drought phase after the deactivation of adopted measures. They are used to restore water resources and the aquatic ecosystem after drought impacts.

These measures are programmed based on drought status determined through the indicators system. A five-stage classification is commonly used for drought response measures' adaptation [5]:

- *Normal status*: This phase is for planning, and strategic and long-term measures are applied in this phase. These measures include water demand management, water usage efficiency measures, and development of hydraulic infrastructure for increasing the storage and regulation capacity of the watershed, for promoting the use of nonconventional resources (e.g., treatment and reuse facilities).
- *Pre-alert status*: In this phase, the objective is prevention of water bodies from deteriorating through activating specific drought response measures while the water demand is met. The measures used in this status are commonly information and control measures, as well as voluntary water-saving measures.

- *Alert status*: In this phase, drought is progressing and it is needed to apply more severe measures. It is the intensification of the pre-alert status; still, the first priority is to prevent water bodies from deteriorating. The measures used in this status emphasize on saving water. Regarding the socioeconomic situation and impacts, demand restrictions can be applied in this phase. Special attention should be given to areas with high ecological value to prevent their deterioration.
- *Emergency* (*extreme*) *status*: If even after application of previous prevention measures, the drought situation prevails to a critical status, the emergency situation is initiated. In this phase, water resources are not sufficient for the essential demands supply (even affecting and restricting the public supply), and more severe measures are applied to reduce impacts on water bodies and the environment.
- *Recovery status*: When the drought status terminates, during drought recovery, measures are applied to monitor the system status change from emergency condition to the normal condition to ensure a quick restoration of water ecosystems.

30.4.5 Plan Activation and Termination

The government or local authorities activate the drought emergency response plan when, based on predefined indicators and triggers, the conditions for the drought start stage are met. In this situation, the following actions are initiated:

1. The local media and Internet-based services are used to inform the public about the initiation of the drought emergency response stage.
2. The special and dominant customers (if any) and related governmental organizations on water resources management are notified about the details and reasons for initiation of the drought emergency response stage.
3. If specific provisions of the drought emergency response plan are activated, the related organizations should be notified for providing the needed support for effective application of these provisions.

Local authorities and customers should follow the drought emergency response stage imposed by the government. In other cases, local authorities can decide by themselves about the implementation of a drought response plan, even though only some triggers for the stage are met. Decision may be dependent on weather conditions, the time of the year, the anticipation of replenished water supplies, or the anticipation that water demands will be met by additional facilities. In any case, a complete documentation of the decisions and the reasons should be provided.

The drought emergency response plan is terminated by local authorities when the conditions for termination are met or at their discretion. For termination of a drought emergency response stage, the following activities should be performed:

1. The public is informed about this termination through local media and Internet-based services.
2. The specific and dominant water customers and related organizations in the government are informed about this termination.
3. The related organizations are informed about the termination of the mandatory provisions (if they were activated before).

The drought emergency response plan may remain activated even though termination criteria and triggers are met because of factors such as the time of the year, weather conditions, or the possibility of situation change for drought continuation. The reason for this decision should be documented [23].

30.5 Monitoring Drought Plan

The main issue in an effective and successful drought response plan is monitoring (the continuous observation and evaluation) of the plan's application, performance, and effectiveness. The concepts that should be considered in a drought response plan are further discussed in this section.

30.5.1 Establishment of Drought Management Organizational Structure

In the development of a drought response plan, it is needed to establish an expert entity, committee, or working group to identify drought impacts, evaluate drought responses, and measure drought impacts. Furthermore, good coordination among authorities and entities related to drought management and the active participation of appropriate stakeholders are necessary for a participatory approach and a responsible reaction from society. Experts and stakeholders should emphasize on the necessity of drought response plan application.

The organizational arrangements and allocation of roles and responsibilities during a drought event should be determined for a successful drought response plan. The following responsibilities in particular should be determined [26]:

- Monitoring of drought development
- Application of measures based on the plan as the drought develops and recedes
- Monitoring of the effects and effectiveness of drought measures
- Documentation and reporting to appropriate authorities

30.5.2 Continuous Monitoring of Water Status and Emergency Drought Plan Application

An important issue in drought management is the continuous monitoring and evaluation of drought development. The on-time detection of a drought onset is dependent on permanent monitoring of the critical components of the basin's water balance even in the normal situation. It is needed to permanently collect, store, and process data related to precipitation, river flows, dams' storage, inflows and outflows, change in water levels in aquifers, evapotranspiration, and hydrochemical and biological elements.

In case of severe droughts with serious environmental and ecological impacts, additional sampling might be done to determine the impacts on different components of the system. Therefore, special points for drought monitoring can be added to hydroclimatic monitoring networks to provide needed information for the drought follow-up, in addition to the regularly obtained data for water resources management purposes.

In addition to water resources monitoring networks, the drought response plan needs to include a follow-up program to check the use of appropriate responses and their effectiveness in the reduction of drought impacts. This purpose can be achieved by setting indicators in accordance to the type of measures that drought response plans include. The main categories of these indicators are as follows:

- Preventing indicators: Indicators such as reservoir storage, surface flows, groundwater levels, and precipitation.
- Operative indicators: Indicators linked to the water demand and supply, as well as to environmental protection.
- Management and organizational indicators: Indicators to check the process of drought response plan application and its advances.
- Furthermore, some indicators can be used to provide information about the following issues:
  - Providing required agencies for management and follow-up
  - Providing required staff and material
  - Developing functioning protocols and rules
  - Documenting experiences during drought and preparing post-drought reports
  - Applying actions planned for community recovery after drought
  - Coordinating among expert authorities

30.5.3 Continuous Forecast of the Expected Water Resources

Providing continuous, accurate, and precise forecasts on available water resources in next time steps (months or even year) is necessary to select appropriate measures during droughts based on drought emergency response plans. To achieve such a prediction, the development of an appropriate entity with links to the competent body for the region is necessary. For forecasting, it is needed to statistically analyze the current available data on precipitation, river flows, reservoirs, and aquifer levels using proper stochastic simulations, and provide estimations of water resources availability and corresponding probability of drought occurrence.

30.5.4 Continuous Evaluation of Water Demands

Water demand to fulfill different domestic, industrial, irrigational, and other needs should be continuously monitored and evaluated to determine actual needs and consumption effectiveness and to estimate water losses, including unaccounted and wasted water. In drought response plan development, it is needed to establish the minimum limits for each category of use and provide an agreement on them among different users before drought onset. It should be mentioned that water supply priorities change under drought conditions based on environmental, population health needs, and strategic, economic, national, and social criteria as part of a drought response plan.

30.5.5 Improving the Effectiveness of Water Use and Mitigation Measures

The measures used for water use efficiency improvement are divided into two groups: those measures that improve the performance of water distribution infrastructure and those measures that improve water use efficiency at the stakeholder level. From another approach, these measures can be divided into structural (improvement of existing infrastructure) and nonstructural (e.g., organization and management improvement, more knowledge about water losses and management, establishment of management information systems, more accurate calculation of crop water demand and adjustment of water allocations, optimization of water allocation timing, promotion of user initiatives for improvements, and tariff systems) measures.

Finally, monitoring mechanisms are used to determine the performance of the drought response plan in achieving its predefined purposes and reducing the adverse impacts of drought. This evaluation is usually performed as an ex-post analysis of each drought event to assess the outcomes of the drought response plan and to learn from the experiences during drought. At the end of the evaluation process, the necessary corrections for future plan revisions are recommended. The assessment of the economic impacts of drought events is also included in this monitoring mechanism.

30.6 Virtual Drought Exercise

When facing droughts, using sound strategies in real time could decrease drought damages considerably. However, to ensure the effectiveness of the proposed response plans, it is needed to evaluate them before the drought event happens. For this purpose, a Virtual Drought Exercise (VDE) can be used. VDE is a strategy for pre-drought evaluation of response plans and can increase communities' preparedness in dealing with droughts. VDE provides decision-makers with the opportunity to simulate disasters without taking any risk [9]. The shared vision model can be used for VDE and make it a more effective planning, evaluation, and response mechanism.

The basic concept of VDE is simple: People who will be involved in future droughts' management gather in a room and practice their responsibilities during a virtual drought. The degree to which the simulation becomes realistic depends on the participants and their representation of stakeholders' position and the efficiency of the developed shared vision model in simulating agencies and stakeholders' utilities.

VDE is like a game; it puts people in an environment to make joint decisions regarding hypothetical options. In VDE, people can see how the water system responds to their decisions and can change the operating rules in a way to improve the system's performance. It should be noted that the effects of drought responses are not simulated just by the shared vision, but through reactions, discoveries, and interplay of participants in VDE.

The main considerations in VDE development are as follows:

- Precise determination of the exercise's objectives
- Preparation of a complete list of participants
- Provision of the required information to participants
- Determination of the format, agenda, and rules of the exercise
- Definition of a virtual scenario
- The usage of the shared vision model for interaction simulation and evaluation
- Improvement of the ability to respond to drought

The main outcomes of VDE are as follows:

- Better understanding of roles, responsibilities, and interests of the participants
- Improved communication among those included in the drought response plan
- Identification of main weaknesses of the plan and how they can be refined

VDE includes three main phases of briefing, simulation, and debriefing. In the briefing phase, the objectives are stated, the rules are described, and the initial conditions are introduced. In the simulation phase, participants utilize the shared vision model to evaluate decisions, discuss drought management strategies, and negotiate a decision. Finally, a decision is made and implemented in the shared vision model. Based on the model results, the decision's effectiveness is evaluated, and this procedure is repeated until the drought scenario terminates. At the end of this phase, the participants' information on the drought response plan is updated. In the debriefing phase, the lessons learned through the exercise are evaluated and put into action in operational, institutional, and modeling procedures.

30.7 Summary and Conclusions

Drought is a normal, recurrent feature of any region's climate and is generally defined as a temporary reduction in the average water availability. Drought has special characteristics that make it different from other natural disasters. The main features of drought are its slowness of onset, its commonly long duration, and its nature of affecting a large area. It is not possible to prevent droughts from occurring, but the resulting impacts can be highly mitigated through application of appropriate monitoring and management strategies previously planned in a drought management plan (DMP). In drought management, both aspects of risk and crisis management are taken into account. DMPs are developed based on the characteristics of droughts in the region, their effects, and the effectiveness of mitigation measures applied in previous drought events. An important component of a DMP is drought emergency response plan.

In the multilevel approach to a drought response plan, appropriate indicators and corresponding thresholds need to be established in order to identify drought onset and decide about the measures to be used in order to prevent and mitigate drought effects on the water status.

A specific program of measures can be defined in a drought response plan, to be applied for intensifying the monitoring and management of water resources to guarantee water supply and its uses. The objective is to maintain the minimum essential, and ideally reasonable and sustainable, demand for water without impacting the environment.

In a drought response plan, a dynamic framework is developed for preparing and responding to drought. This framework has three basic elements: (1) a drought early warning system, (2) a drought stages scale with clear thresholds adjusted to indicators' state, and (3) a set of mitigation measures for each drought stage to achieve that stage's drought mitigation objectives. Transparency and public participation are important issues in drought response development.

The early drought warning system is developed based on hydrological indicators, as simple as possible in a way representing the spatial and temporal situation of droughts, allowing drought onset identification, control, and severity assessment. Since a single indicator cannot completely reflect the intensity and severity of drought and its potential impacts on the great diverse group of users, a set of indicators are used for drought response plan development.

Drought indicators and thresholds are of high importance in a drought emergency response plan because they are used to identify and monitor drought conditions, to determine the timing and level of drought responses, and to characterize and compare drought events. The proposed multilevel approach developed based on indicators should be evaluated before and after drought events. The pre-drought evaluation can be done through VDE.

Measures applied during droughts are grouped into five categories: (1) preventative, (2) operational, (3) organizational, (4) follow-up, and (5) restoration measures. The measures' application program is determined based on the drought status obtained through the indicators' system. Optimal measures should be determined for this purpose based on the drought impacts and the measures' cost and effectiveness. Control and water-saving measures (voluntary and mandatory) are commonly used in initial stages of drought. Because of drought, water supply shortages for different users are probable, and thus, additional measures are used to ensure consistent public supply and minimize impacts on the environment. In the drought recovery phase, measures are applied to guarantee a restoration of water ecosystems. Different structures needed for monitoring a drought response plan should be developed to ensure the plan's effectiveness. The main component of the monitoring system would be the evaluation of the response plans' application process and their effectiveness (post-drought evaluation) and determination of the refinements needed in the plan.

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Coping with Drought

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Abstract Drought is a natural phenomenon caused by a meteorological anomaly, modified by the physical properties of a catchment. In order to prepare for drought and cope with it, the first step is to formulate a strategy and action plan. To put drought preparedness and long-term planning and mitigation into operation, it is proposed to establish a National Drought Management Center. The Center forms an appropriate drought management task force as a coordinating mechanism among stakeholders and decision-makers. Under the new strategy, there are good prospects of setting up a coherent drought management system with clear coordination mechanisms. For drought planning, a management cycle with four drought stages and phases is assumed. The prevailing conditions for each of these drought stages and program phases start from normal conditions through to drought alert, drought alarm, and emergency. The implementation of the plan is to identify current drought severity in different provinces of a country, as well as to determine the onset, duration, and end of the drought. For effective plan implementation, the expected tasks and responsibilities are assigned well in advance to each entity or stakeholder before the drought has occurred. The proposed *Guidelines for Drought Mitigation and Preparedness Planning* represents a comprehensive list of potential drought mitigation actions. Generally, it is better to consider a proper plan that has formed technically while considering successful experiences all over the word, which has then been enhanced and developed for local purposes, on the basis of definite facts of a specific region.

31.1 Introduction

Drought is a natural phenomenon caused by a meteorological anomaly, modified by the physical properties of a catchment [6] and intensified by extensive use of water. Drought simply means lack of water; water that normally would be available in a region and to which nature and mankind have adapted over centuries [6]. Drought is a complex phenomenon that caused more deaths during the last century than any other natural disaster did [2]. Water scarcity and drought are among the biggest challenges facing the world's social and economic security in the future [3], especially in arid and semiarid regions including fragile ecosystems.

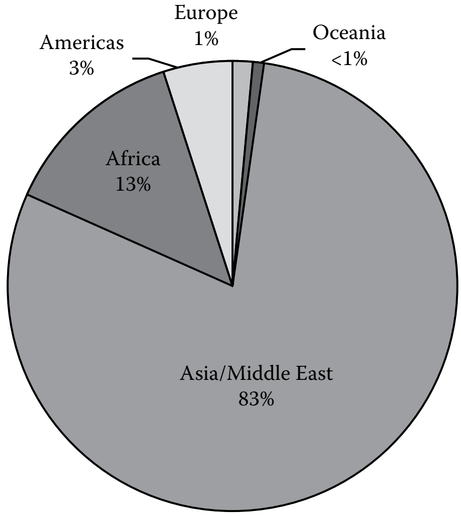

FIGURE 31.1 Percent of total number of people affected by drought from 1900 to 2004 by continent. (From Food and Agriculture Organization of the United Nations (FAO), Regional Office for the Near East, Cairo, Egypt, and National Drought Mitigation Center University of Nebraska-Lincoln, Nebraska, USA, *The Near East Drought Planning Manual: Guidelines for Drought Mitigation and Preparedness Planning*, Rome, Italy, 2008, 59pp.)

As shown in Figure 31.1, Asia and Africa rank first among continents in which a number of people are directly affected. In these continents, drought has affected more people than any other natural hazard has during the last decades. Drought caused widespread crop failures and livestock losses; increased drinking water and food shortages; increased disease, stress, and other social problems; reduced hydropower generation and increased soil erosion and fire occurrence; forced mass migrations to urban areas and other countries; and generally increased debt and reduced security at the local and national levels [2].

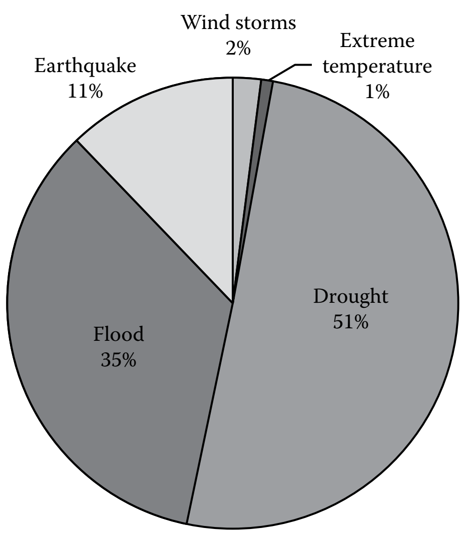

FIGURE 31.2 Percent of total number of people affected by natural disasters from 1978 to 2007 in the Near East region. (From Food and Agriculture Organization of the United Nations (FAO), Regional Office for the Near East, Cairo, Egypt, and National Drought Mitigation Center University of Nebraska-Lincoln, Nebraska, USA, *The Near East Drought Planning Manual: Guidelines for Drought Mitigation and Preparedness Planning*, Rome, Italy, 2008, 59pp.)

Hence, drought planning and preparedness are essential components in coping with consequences such as desertification and climate change, and in increasing the resiliency and sustainability of communities and nations to natural hazards. Because of the integrated nature of these issues, increasing efforts to better prepare for and respond to drought have the potential to help address a wide variety of other management issues [2].

The results of focusing on proactive drought planning are reducing drought impacts and expenditures, and also supporting capacity building, collaboration, and sustainable development [2].

Drought preparedness is defined as established policies and specified plans and activities taken before a drought to prepare people and enhance institutional and coping capacities, to forecast or warn of approaching dangers, and to ensure coordinated and effective response in a drought situation [2] (Figure 31.2).

31.2 Starting to Cope with Drought

31.2.1 Drought Preparedness Strategy

In order to prepare for drought and cope with it, the first step is to formulate a strategy and action plan. A national drought action plan is a document which is simply formulated and supplemented with attachments and appendices of detailed information where necessary so that it can be easily implemented by the concerned stakeholders. The plan should have the important characteristics of being ready for and responding to a declared drought situation; have clear procedures and measures for managing the drought crisis and its aftermath; and allow good communication before, during, and after the drought. The drought plan also contains long-term policies to be implemented in the event of a future drought.

The lack of strategic drought planning and a delay in decision-making, with the associated impact on management cost, have led to costly remedies of the impacts of drought, that is, crisis management is more expensive than more proactive risk management [3] with necessary preparedness. Depending on the geographical settings and area scale (local, national, and regional), this strategy may vary. Despite the variability of plans, the main objective of a national drought preparedness strategy is to allow for the implementation of three kinds of measures:

1. Mitigation, including thorough contingency plans to minimize drought impacts on livelihoods
2. Relief for the welfare of those targeted communities hit by drought
3. Rehabilitation of production systems after the drought

As drought conditions escalate from normal to emergency situations, the drought action plan associated with the preparedness strategy should indicate the types of measures to be implemented by the concerned stakeholders for each drought situation [3]. Because this joint objective may vary in different places and communities, special experiences in countries are useful guidelines. The proposed framework is derived from the national drought preparedness strategy for Iran* [3].

The following are the main components of the framework for establishing the national drought preparedness strategy:

- Creating a national drought management center
- Adopting policies to support drought resilience and reducing vulnerability
- Enhancing institutional coordination mechanisms for drought management
- Developing national capacity for drought planning, mitigation, and response

* The main subgroups charged with drought-related activities are under the Ministry of Jehad Agriculture (MoJA), the Ministry of Energy (MoE), and the Islamic Republic of Iran Meteorological Organization (IRIMO).

31.2.1.1 Creation of a National Drought Management Center

In order to put drought preparedness and long-term planning and mitigation into operation, it is proposed to establish, under the legal framework of the "Master Plan for Relief and Rescue" and within the MoJA, a National Drought Management Center (NDMC) based on a model which is simple in structure and flexible in function. The Center's structure would comprise three specialized, operational working groups, as follows: (1) Drought Early Warning and Monitoring Group, (2) Drought Risk and Impact Assessment Group, and (3) Drought Planning, Mitigation, and Response Group.

The primary function of the Center is to ensure working linkages between MoJA and the stakeholders concerned with drought management. Thus, the Center is proposed to form an appropriate drought management task force as a coordinating mechanism among stakeholders concerned with drought at national and provincial/district levels.

The Center will have a National Steering Committee for Drought Preparedness (NSCDP) and a Board of Trustees (BoT) that has linkages with and authority from the highest possible level of decision-making. The Center's Board of Trustees will assume policy making, interagency coordination among stakeholders at all levels, and approval of funds. The Board Members will be the Minister of Jehad-e Agriculture (Chairman), the Interior Minister, the Energy Minister (Water), the Transportation Minister (or Iran Meteorological Organization Head), the Environment Department Head, the Iranian Space Agency Head, and the Management and Planning Organization Head. The members can also designate senior persons from their institutions to represent them on the board.

The Center's NSCDP has the responsibility of providing expertise and advice to the Center on technical matters; evaluating past sectorial action plans and activities and approving proposed new ones; and making relevant implementable recommendations to the Board of Trustees. Members of the NSCDP are multidisciplinary experts from the concerned line ministries, stakeholder institutions, and organizations dealing with drought management at the country and province/district levels.

The members include Deputy Ministers of MoI (DTF Head), MoJA (Agronomy), MoE (Water), MoH; Deputy Heads of Management and Planning Organization (MPO), DoE, IRIMO, AREO, RFWO, WRMO (Water Resources Management Organization/MoE), ISA; and the Heads of the relevant Universities, Research and Development Centers, and Engineering firms working on drought preparedness and water management issues. The NSCDP plays a major role in proposing drought management policies and making recommendations for their implementation.

31.2.1.2 Policies to Support Drought Resilience and Reduce Vulnerability

The proposed policies to reduce drought vulnerability are geared towards (1) integrated water and drought management (in agriculture, including increasing water use efficiency and water productivity*); (2) drought management policies for irrigated agriculture, rainfed agriculture, and livestock; (3) stakeholders' participation and support to develop a drought plan; and (4) drought information, public education, and awareness.

31.2.1.2.1 Integrated Water and Drought Management Policies

The policies associated with greater resilience to drought are generally linked with water resources planning and management. Because of the close relationship between water scarcity and drought, drought management should be an essential element of national water resources policy and strategies. Strategic planning of water resources management for drought preparation and mitigation in the agricultural sector and for other uses consists of two categories of measures, both planned in advance for the long and short term, depending on the kind of policies adopted.

Long-term actions imply planning for a set of appropriate structural and institutional measures to reduce the vulnerability of water supply systems to drought, that is, to improve the reliability of each system to meet future water demands for drinking, agriculture, hydropower, and other uses under drought conditions.

* More than 90% of the water is used in the agricultural section.

Increase of water storage capacity, adoption of water-saving technology, and recharge of groundwater are examples of long-term measures. Depending on the severity of drought, long-term actions may or may not completely eliminate the risks associated with it. They are supplemented by short-term measures which correspond to the actions taken during implementation of a drought contingency plan.

Short-term measures are actions that try to face the onset of a drought event within the existing framework of infrastructures and management policies. An effective water resources management plan for drought mitigation is the one that has an optimal combination of both short- and long-term measures. Such measures can be combined to form three categories of policies: (1) supply management policy, (2) demand management policy, and (3) drought impact minimization policy. All policies should consider end user concerns and natural ecosystem needs. The measures related to supply management aim at increasing the available water supplies, whereas those pertaining to demand management aim at improving the efficient use of available resources and reduction of water consumption. These two categories of measures are designed to reduce the risk of water shortage due to a drought event, while the third category is oriented to minimize the environmental, economic, and social impacts of drought.

31.2.1.2.2 Drought Management Policies in Irrigated Agriculture, Rainfed System, and Livestock

In the agricultural sector, soil and water conservation is a major policy issue for drought management and impact minimization. An effective drought preparedness policy should provide a comprehensive, consistent, and integrated approach at all levels to reinforce the capacity of farmers and herders to adopt self-reliant, sustainable farm management technologies in order to minimize impacts on irrigated and rainfed agricultural systems, livestock, and natural ecosystems. The policies for minimizing drought impacts on irrigated agriculture include improvement of water use efficiency and water productivity; and adoption of soil and water conservation measures. Minimizing the impacts on rainfed agriculture requires adoption of sustainable farm and livestock management practices. Minimizing impacts on livestock while preserving natural ecosystems requires improvement of feeding and health conditions of the herds and development of long-term pasture and forest management plans. Regardless of the agricultural production system, the policies should aim at developing operational systems for early warning of drought, developing watershed management practices, raising public education and awareness about the prevailing water scarcity and drought conditions, using indigenous knowledge for drought mitigation, and adjusting the legal and institutional framework of integrated drought and water resources management in the country.

For irrigated agricultural systems, the use of drip irrigation, sprinkler irrigation, growing of water-efficient crops, control of weeds that compete with crops for water and nutrients, wastewater reuse, metering and pricing policies, and other water-saving measures may achieve water conservation. In rainfed systems, supplementary irrigation from harvested water or groundwater resources can play a critical role in combination with rainfall in increasing and stabilizing crop yields in the dry lands. Depending on the production system, emphasis should be placed on the use of drought-resistant seeds, appropriate soil tillage and technological packages for fertility, efficient water use techniques for crops, improved crop yield and quality of harvested products, reduced postharvest losses, and improved livestock feeding and health conditions.

Loans and drought insurance schemes should also be developed to enable farmers and herders to manage within the constraints of prevailing seasonal climate conditions. Specific government assistance may be required only when the risks involved begin to exceed those that can be reasonably addressed by the farmers and herding communities. Success (or failure) of the proposed programs and the measures to promote sustainable agricultural and land use systems should be assessed at farm level in each province and/or district.

The use of indigenous knowledge to support sustainable agricultural land use systems at farm level should also be promoted by government interventions within the proposed national drought preparedness strategy and action plan. In many of the rural areas, surface runoff can be captured and stored in artificial depressions or cisterns. In normal years, these cisterns will contain water during the entire dry season. The ingenious traditional Qanat water system is the ideal way to access groundwater for irrigation and drinking.

Therefore, the policies aimed at encouraging the use of water conservation technologies and indigenous knowledge are important ways to mitigate the effects of drought and to optimize the use of water both under normal and drought conditions.

31.2.1.2.3 Stakeholder Participation to Develop Drought Management Plans in the Agricultural Sector

The strategic water-planning process referred to earlier (supply-oriented policy, demand-oriented policy, impact minimization policy) should take into account concerns of the end users, which are related to drinking water, agriculture, hydropower, industry, recreation, and ecosystem preservation. An important feature of the end user policy is that priorities for water allocation under drought conditions should be clearly stated by the stakeholders' experts participating in the working groups of the NDMC. The working groups include specialists on the subject who use shared-vision methodologies and participatory approaches to develop the views of the stakeholders they represent and to prepare the required strategies and policies for drought mitigation, including public information, education, and awareness.

The coordination mechanism among the stakeholders through the NDMC is designed to offer the services of a Drought Preparedness Task Force which is centrally coordinated to ensure operational linkages between information providers and users, at national and provincial/district levels, through a number of multidisciplinary working groups on those important components of the drought management strategy, that is, drought monitoring and early warning, risk and impact assessment and planning, and mitigation and response.

31.2.1.2.4 Drought Information, Public Education, and Awareness-Raising Policies

Because of its slow onset, drought differs from all other natural hazards and its adequate management requires the detailed integration and interpretation of multidisciplinary information on a daily basis. The NDMC would ensure such integration, with the assistance of operational Provincial Coordination Units (PCUs). In the proposed framework, the Center's information system integrates relevant data from the three working groups (monitoring, impact assessment, planning), the provincial coordination units, as well as from experts in the universities/research centers and in private engineering firms. The provincial coordination units receive signals, tools, and methodologies from the Center and send back relevant information on drought management in the provinces and districts to be incorporated into the policies.

31.2.1.3 Institutional Coordination Mechanisms for Drought Management

Under the new strategy, there is good prospect for setting up a coherent drought management system with a clear coordination mechanism:

- Coordination of the early warning and monitoring group is the task of IRIMO given the organization's expertise and network in weather forecast and seasonal climate prediction, and its ability to work with the two other stakeholders (MoJA, MoE).
- Coordination of the risk and impact assessment group is proposed to be performed by the Deputy of Agronomy/Ministry of Jehad Agriculture (MoJA) in accordance with its expertise and capacity in this field, but also given the fact that most impacts are on agriculture, livestock, pasture, and forest.
- Coordination of the planning, mitigation, and response group is led by the Deputy of Water/Ministry of Energy (MoE), given the available expertise in long-term water planning and management, and also considering the fact that an integrated approach to water and drought management should prevail in any national drought mitigation strategy in the country.
- Coordination between national and provincial/district levels is the responsibility of the Center with its three working groups and provincial coordination units, in collaboration with stakeholders' provincial executive structures.

The NDMC and its main stakeholders for early warning and monitoring (IRIMO), risk and impact assessment (MoJA), and planning, mitigation, and response (MoE) have the responsibility of coordinating the development of the national drought action plan. This drought management tool is the main output that the Center and its stakeholders would produce for the decision-makers and drought managers. Success in the elaboration and implementation of the action plan hinges on the degree of collaboration between these stakeholders for collecting, analyzing, and delivering the data related to their respective sectors. The stakeholders will also be responsible for contributing to the elaboration and implementation of the action plan as it relates to their respective fields. In order for the Center to evolve to the regional level, its structure and mandate will have to be reviewed in order to incorporate this dimension (involvement of the other countries in the different elements of the structure).

The Center would greatly impact individual stakeholders among line ministries (MoJA, MoE, MoI, MoH, DoE, DTF, etc.) and organizations (IRIMO, ISA, Agricultural Products Insurance Fund, Agricultural Bank, etc.) in the sense that these stakeholders would have to be more responsive and take necessary measures for drought mitigation and response in a timely manner. The stakeholders should also consider the Center's report as a "Ministry technical document" for operation and action, particularly by making the necessary resources, information, and expertise available to its working groups and provincial coordination units, for implementing the relief programs and mitigation activities. The stakeholders should recognize and execute the recommendations and actions of the Center's proposed plans for the development of water resources, development of sustainable agriculture, and conservation of natural resources according to the prescriptions of the drought plan before drought occurs.

31.2.1.4 Drought Information Management and Communication System

Key providers of basic information for drought management are IRIMO, MoE, MoJA, MoH, DoE, MoI through DTF, MoCIT through ISA, Provincial Water Authorities, Provincial Jehad Agriculture Organizations, and national/provincial structures of DoE. Contribution from universities, research centers, and private engineering firms consists of providing the relevant updated information about methodologies and tools for risk analysis, impact assessment, and vulnerability, and on long-term drought planning and management policy issues. They also provide the training packages for all these issues and ensure the linkage with regional/international organizations working on such issues.

Basically, IRIMO will systematically provide a summary of historical drought comparisons, a summary of actual precipitation data compared to normal, a summary of extended forecasts and climatic maps on current weather conditions, and develop probable drought conditions.

31.2.2 National Drought Action Plan and Contingency Planning

31.2.2.1 Development of a National Drought Action Plan

Under the present drought preparedness strategy, the proposed national drought action plan contains the following elements:

- The drought-monitoring approach with a description of the processes involved in identifying the extent and severity of drought conditions in different provinces of the country
- The stages of drought and expected responses and activities, including impact and vulnerability assessment, short-term relief and/or long-term mitigation measures which are adapted to each drought stage
- The roles of government and nongovernment agencies/institutions and of drought-related citizen's groups (e.g., Iran Red Crescent Society) in plan implementation
- The drought information management and communications system to continuously inform stakeholders about drought development stages and mitigation measures, to ensure public education and awareness, and to gather the required information for adjusting the national plan on a yearly basis

In addition to these elements and for the purpose of its future implementation, the drought plan should contain legislative and resource needs as locally assessed by the stakeholders at the province/district levels; and also the proposed policies that will limit vulnerability to drought and improve the country's resilience to this natural hazard.

For drought planning, especially in the agricultural sector, a management cycle with *four drought stages and phases* is assumed:

1. Normal conditions and drought advisory phase
2. Drought alert and conservation phase
3. Drought alarm and restriction phase
4. Drought emergency phase

The prevailing conditions for each of these drought stages and program phases start from normal conditions through to drought alert, drought alarm, and emergency.

The "normal conditions program phase" is referred to as the *drought advisory phase*, since *the drought-planning process should be activated* under normal conditions rather than when drought has occurred as is the case in the present *crisis management* program. Drought alert is the signal for the *conservation phase*, drought alarm for the *restriction phase*, and drought emergency for the severe *crisis situation*. Specific triggers apply for each drought stage to signal the drought alert, drought alarm, or drought emergency phase. Here, the role of the Drought Early Warning and Monitoring Group is of considerable importance since it has to send the right signals at the right times for actions to be taken.

The Drought Risk and Impact Assessment Group is activated after receiving alert signals about drought from the monitoring system. The assessment group evaluates the spread of drought, assesses its impacts, as well as proposing basic information for the contingency planning experts as and when necessary and making an evaluation of the executed drought plans. This group also evaluates the usefulness of existing methodologies and develops, in collaboration with universities, research centers, engineering firms, and international centers, new tools for drought risk and impact assessment and for determining vulnerability profiles of drought-stricken target groups or economic activities.

Based on the evaluation provided by the risk and impact assessment and the early warning and monitoring working groups, the Drought Planning, Mitigation, and Response Group provides guidance for developing national/provincial plans for drought mitigation, relief, rehabilitation, and response. These plans propose short-term actions and measures for emergency conditions, as well as medium- and long-term actions to reduce vulnerability.

31.2.2.2 Provincial/Local Contingency Planning

For drought contingency planning at the province/district levels, the foundations are (1) system-specific drought indicators and triggers, (2) identification of relevant responses including mitigation and long-term measures; (3) stakeholders' participation in developing the plans, and (4) public education and awareness.

Drought contingency plan is an important part of the drought preparedness planning effort. The national drought action plan as well as the provincial contingency plans should be simply formulated, supplemented with appendices of detailed information where necessary, and have the following characteristics:

- Be ready for and respond to a declared drought situation
- Have clear procedures and measures for managing the drought emergency and its aftermath
- Ensure communication before, during, and after the drought emergency has been declared

In order to yield tangible outputs, drought managers have to undertake coordinated actions along the following 10-step methodology for emergency planning (Table 31.1).

The proposed 10-step methodology for drought contingency planning effort at the provincial/local level is to elevate the public's perception about the proposed measures in the national drought plan during the conservation phase, the restriction phase, and the emergency phase. It should also allow for large public participation in adapting such measures to their real situation in the district or province.

TABLE 31.1 10-Step Methodology for Emergency Planning

Step No.	Strategy
Step 1	Identify drought response participants and establish their roles and interventions, resources, and concerns
Step 2	Evaluate the risks that may result in emergency situations in the drought-impacted communities and define options for risk reduction
Step 3	Have participants review their own drought emergency plan, including communications, for adequacy relative to a coordinated response
Step 4	Identify the required response tasks not covered by existing drought plans
Step 5	Match tasks to resources available from the identified participants/institutions
Step 6	Make necessary changes to improve existing emergency plans, integrate them into an overall drought emergency plan, and obtain agreement of concerned communities
Step 7	Commit the integrated community plan to writing and obtain endorsement for it and relevant approvals for its implementation
Step 8	Communicate final version of integrated plan to participating groups and ensure that all emergency responders are trained
Step 9	Establish procedures for periodic testing, review, and updating of the contingency plan
Step 10	Communicate the integrated contingency plan to the general community at the province/district level

By doing so, the local authorities and representatives tend to capture, through their contingency plans, decision-makers' attention to the challenges of drought in their province or district, and to secure fund, legislation, or additional resources accordingly.

All provinces should develop their own drought preparedness plans with the Center's guidance and technical supervision.

A participatory top-down and bottom-up approach should be used to transmit to the provinces the necessary tools for early warning and monitoring; methodologies for risk and impact assessment; and drought-planning tools. Feedback from the provinces and the districts about developing drought conditions will reach the Center through its Drought Information Management and Communication System referred to earlier. This system will secure information flow and communication between stakeholder experts at the central and provincial/local levels. The Center will develop the drought information system in the form of databases, data analysis methodologies for generating decision-making tools, and information synthesis for public awareness. The decision-makers, the drought managers, and the public will therefore be continuously kept updated about developing drought conditions at the national, provincial, and local levels. The decision-makers will also have guidelines for managing the relief program and for drought planning in the short and the longer terms.

An important feature of a provincial drought plan is the definition of drought triggers specific to each *province* that can be used separate from, or in conjunction with, drought triggers at the *national* level. For example, system-specific drought triggers for irrigated agriculture may include information on reservoir levels, number of days of water supply remaining, and average daily water use. Other *specific local triggers* for pastoral systems may relate to feed reserve and watering points for livestock. Specific triggers may also relate to food security for rural communities in severely impacted areas of different provinces. Accordingly, each drought situation will require specific mitigation measures.

31.2.2.3 Implementation of the National and Provincial Drought Action Plans

The implementation of the plan is to identify current drought severity in different provinces of a country, as well as determining the onset, duration, and end of the drought.

Responsibilities of the various drought management instances and stakeholders' participation for executing the drought plan at national and provincial/local levels are also stated.

The main outputs of plan implementation are summarized in Table 31.2. It relates to continuous assessment of drought development stages, triggering mechanisms for drought declaration, impacts assessment and vulnerability, public information on drought development and response options, and information for updating the plans.

TABLE 31.2 Outputs of Drought Plan Implementation in Relation to Prevailing Conditions

Conditions and Drought Stages	Output No.	Output Content
Normal Conditions and Drought Advisory Phase	1	Report on specific needs for trigger declaration: drought alert and conservation phase
	2	Evaluation report on impacts in areas entering Stage 1 drought status (drought alert)
	3	Annual review of drought plan with recommendations for future improvements
Stage 1 Drought Alert and Conservation Phase	4	Update drought status maps and develop information needed for trigger declaration of Stage 2 drought
	5	Prepare media information and public awareness campaign on conditions to enter drought alarm and restriction phase
	6	Annual report with synthesis of monthly reports on conditions and recommendations on drought response options
Stage 2 Drought Alarm and Restriction Phase	7	Update drought status maps and develop information needed for drought trigger declaration of Stage 3 drought
	8	Report on developing drought situation and impacts, restrictions measures, and response options
	9	Press release on drought development and response options in connection with drought emergency declaration
Stage 3 Drought Emergency Phase	10	Report to update drought status and develop information for mapping the areas concerned with drought stages 1, 2, or 3; and/or normal conditions
	11	Develop synthesis report on implementation of drought plan, with identification of areas of concerns and of vulnerable groups or economic activities
	12	Finalize report necessary for emergency declaration; President/governor makes drought emergency declaration; governors implement emergency powers as needed
Receding From *Drought* to *Normal* Conditions	13	Report to recommend needs for additional drought monitoring, early warning, and prediction tools
	14	Report to recommend needs for additional drought impact assessment tools
	15	Report to assess the National Drought Plan implementation and recommend future improvements of the plan including alternative options

Based on this continuous assessment, *drought declaration* by the Office of the President at national level or by the Governor at provincial level is then technically cleared by the Center, before being politically handled by the Disaster Task Force (DTF). The formal declaration of drought is a key issue which the plan addresses by linking objective indicators of drought alert, drought alarm, and drought emergency to operational management actions.

For effective plan implementation, the expected tasks and responsibilities are assigned well in advance to each entity or stakeholder before the drought has occurred. When normal conditions prevail, the NDMC continues its activities to specifically address drought preparedness issues through its working groups for early warning and monitoring, risk and impact assessment, and drought planning. These instances are assigned the tasks of performing under "normal weather conditions," "drought conditions," and "receding from drought to normal conditions." For each of these program phases, the tasks are performed regarding data collection and analysis by key stakeholders involved in drought management: IRIMO, MoE, MoJA, and ISA. Then, the working groups perform drought activities in terms of drought characterization and risk analysis, impact and vulnerability assessment, evaluation of previous relief programs, and drought planning/updating of existing strategies and action plans.

Evaluation of drought impacts on water resources and planning for adequate water supplies is of considerable importance since drinking water for human and livestock remains the top priority under drought conditions. With regard to agriculture, attention should be paid to define *priorities* for irrigation water allocation. Perennials such as orchards and high-value cash crops such as saffron should take priority over field crops and fodder. Priority should also be given to those farmers using more efficient irrigation and water-saving technologies over surface water irrigation techniques. Further, those communities that maintain the use of the ingenious traditional *Qanat* water system deserve more attention in the planning process since the expansion and maintenance of the Qanats could yield greater access to drinking water as well as irrigation of valuable crops and orchards. Changes in cropping pattern, such as discarding rice cultivation in water-scarce areas, and policies aimed at encouraging water conservation measures should also be implemented.

31.2.2.4 Role of National Drought Management Center in Drought Preparedness

The Center prepares reports, fact sheets, or maps on the *onset*, *duration*, *end*, and *impacts* of the drought using information regularly produced by the stakeholders' experts within the three working groups at national level and their related provincial coordination units described earlier. The proposed institutional arrangements to produce these tools to aid decision-makers in drought management will only work well when there is good coordination and communication between ministries, agencies, and organizations at all the various sector and system interfaces. The issue of institutional coordination and communication between stakeholders is particularly important for planning and implementing the integrated drought and water management policies within the national drought preparedness strategy.

Developing a website for dissemination of drought information through the Internet is also an important output which would greatly help achieve the goals of the Center's communication effort among its stakeholders. The other important role of the NDMC is to coordinate training programs, seminars, and workshops on important issues of drought preparedness, mitigation, and response. The Center would therefore require operational support for its specialized working groups and related coordination units from the line ministry agencies, centrally and at the province/district levels. Scientific and technical support would be the role of national research centers and universities, and would also be within the framework of regional and international cooperation program on drought management.

31.3 Practical Methods of Controlling and Coping with Drought

31.3.1 Practical Methods of Coping with Socioeconomic Problems of Drought

The goal of a well-prepared and well-implemented strategy would be to develop a proper drought preparedness capacity, which, in conjunction with management systems, would involve designing strategic policies for forecasting, creating alarm systems, and increasing the flexibility of a community. However, water shortage is inevitable and in most places that face severe and frequent droughts, it is not possible to provide water before and during drought conditions because of their geographical and natural conditions. Hence, during a drought season, unemployment and immigration rise. So some policies should be created to prepare and compensate the rise in this social problem. In this condition, creating short-term employment and developing alternative livelihoods such as handicraft industries must be considered. Droughts occur gradually, so policy makers and planners have enough time to make appropriate plans for handling the situation. There are a number of issues which could help to prepare a complete plan [7]:

- Identifying the capability of dealing with drought
- Analysis of incomes, investments, financial facilities, and loans
- Consulting with experts and those involved in farm management activities
- Comprehensive programs of drought control which are locally more successful
- Preparing short-term employment plans
- Preparing plans for shortage of water and food [7] to help provide stability in affected communities

31.3.2 Practical Methods of Preparedness and Mitigating the Effects of Drought

The proposed *Guidelines for Drought Mitigation and Preparedness Planning* [2] represents a comprehensive list of potential drought mitigation actions in Tajikistan that might be useful as a successful experience. The list consists of the following points:

- Development of National Program of Hydrometeorological Service in terms of drought forecasts
- Rehabilitation and improvement of current hydrometeorological network
- Improvement of automatic sensors of snow accumulation, air temperature, and precipitation
- Modernization of gathering facilities, processing, analysis, interpretation and operative data dissemination, GIS database development and computer-assisted models of drought and its impact
- Development of state policy at national and regional levels on water resource allocation
- Increasing efficiency of economic mechanisms in water resource management
- Development of differentiated tariffs for water use depending on water delivery costs and so on
- Development of program for the study of water resources
- Introduction of international methods and standards of statistical records of water resources
- Formation of automatic control system and water consumption on the basis of GIS technologies
- Establishment of structures for introducing modern irrigation methods
- Arranging training and seminars and exchange of data with countries that have advanced irrigation technologies and methodologies on drought control
- Amending a system of remuneration of labor
- Amending Law on Nature Preservation, taking into account wide development of private farms, including ecological criteria of land tenure under drought conditions
- Establishment of a social insurance fund for combating desertification and droughts
- Zoning of territory for optimal afforestation with the aim of reducing drought exposure
- Establishment of work group to develop projects on optimal location of windbreaks
- Conducting surveys and approbation of highly productive varieties of wood species
- Conducting agrometeorological surveys for identification of climate impacts on soils and productivity of agricultural crops
- Introduction of fast-ripening, disease-resistant, and heat-resistant varieties (i.e., cotton in Tajikistan)
- Improvement of irrigation efficiency on the basis of water-saving technologies
- Zoning of pastures based on their vulnerability to droughts
- Regulating and optimizing pasture load
- Scientific research on the assessment and forecasting of the climate change impacts on the state and productivity of ecosystems and examples of reference sites of nature (national parks, reserves)
- Improvement of the set of measures on prevention of infectious diseases under drought conditions
- Change of regime of work and rest to reduce time spent outside under maximal high temperatures
- Poverty liquidation, particularly among the most vulnerable drought groups
- Zoning of the territory based on its vulnerability to climate changes
- Strengthening of collaboration on drought forecasting and early warning system improvement
- Development of national concept on drought surveys
- Improvement of existing and development of new mechanisms of coordination for the formation of favorable conditions for the most effective implementation of drought mitigation measures
- Improvement on legislative-normative basis to ease access to documents of different agencies
- Introduction of modern methods of forecasting and modeling droughts
- Establishment of Scientific Coordinating Board on Droughts
- Conducting regular meetings on exchange of experiences between different groups of population
- Implementing programs for science-technical training and preparing highly qualified personnel
- Timely issue of bulletin with information on droughts

- Creation of website for exchange of data on drought at both national and international levels
- Improvement of the system for continuous education of the population on ecological education
- Adoption of normative-legislative basis for improving drought awareness among the public
- Improvement of legislation of community participation in decision-making and data access
- Enhancing the work of Social Ecological Board
- Establishment of Informational Center for Drought
- Alteration of educational ecology programs that were introduced in institutes of higher education
- Issuance of illustrated magazines covering drought issues and other ecological problems
- Preparation of the cycle of TV and radio programs on drought issues
- Improving access to the Internet

These are functions that help the communities to be well prepared for drought. The following are some additional items:

- Risk management instead of crises management
- Preparing the national drought atlas
- Drought statistics and information recording
- Convincing the farmers to make use of the treated domestic wastewater in irrigation
- Coming up with a special fund to support the farmers who are willing to enhance their irrigational method
- Investing on constructing water reservoirs as well as modern irrigation networks
- Training and education of the users and consumers of water on efficient ways of utilizing this resource. General training on this subject is to be a constant part of public education programs
- Provision of adequate storage facilities for better water quality, particularly in the remote residential districts, with priority given to the most drought-susceptible locations
- Preparation of National Drought Mitigation Plan on high priority as well as due attention to the following points:
  - *Maximizing water productivity in all sectors of economic activities, particularly in agriculture*
  - *Increasing above-ground and underground water storage capacities*
  - *Keeping the balance between aquifers discharge and recharge*
  - *Minimizing losses in the conveyance systems, particularly in the residential distribution networks*
  - *Implementing strict control measures for water pollution, especially in water-scarce areas*
- Formation of a National Drought Committee, with members from all the ministries and organizations directly concerned with water-related issues
- Providing drought forecasts, monitoring, and early warning systems for all stakeholders, particularly farmers in the most susceptible areas
- Introducing the right cropping pattern to the region
- Capacity development for farm management strategies to improve crop water productivity through improved agronomic practices, use of genetically improved seeds, and application of software and models
- Improving the irrigation methods
- Proper use of nonconventional water resources
- Extensive crop insurance programs to cover all the major crops in any region, particularly where the farmers are poor and where the local economy is dominated by agriculture
- Saving the genetic heritage and biodiversity of the country
- Provision of water supply for wildlife to discourage their migration due to drought [5]
- Practical methods to increase available water, such as use of nonconventional waters (desalinization, reuse of waste waters, etc.) and relocation and water transfer between watersheds

31.4 Summary and Conclusions

Preparedness for drought is a strategy that should be planned comprehensively. Plans can be designed at different levels, that is, locally, nationally, regionally, and internationally, which involve private and governmental sectors and international organizations at each level.

A proper plan is one that has formed technically while considering successful experiences all over the word, and then been enhanced and developed for local purposes, on the basis of definite facts of a specific region. These facts are geographical and socioeconomic characteristics which vary from place to place. Although a strategy plan is suitable for preparedness, it is not sufficient to cope with drought. Because drought is always accompanied by water scarcity, preparedness plans should be in conjunction with practical managerial plans to mitigate drought effects.

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Integrated Water Resources Management under Water Scarcity

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Abstract Integrated water resources management (IWRM) is not a past paradigm. The fact that the concept has survived decades of scrutiny and is still being implemented globally can be considered a strong proof of its viability as a strategy. IWRM has the same elements as the contemporary concept of sustainable development, which also is an overall strategic approach, rather than a detailed, delivery-oriented technical set of guidance. IWRM could be seen as a subset of sustainable development adapted to the water resources management context. The attractiveness of IWRM lies perhaps in its intuitiveness and the fact that the basic concept is relatively simple, in which case there is no need to change the paradigm. Instead, careful attention should be paid so as not to overcomplicate the concept.

IWRM for water-scarce regions provides a comprehensive view of the complexity and interconnectedness of findings and conclusions regarding the principle strategic approach that contributes to improve the water management in basin level sustainability (1992 Dublin Principles). The chapter attempts to present the IWRM concept in arid and semiarid regions of the world, like Iran, which deal with climate change, population increase, and mismanagement.

32.1 Introduction

Water is an essential natural resource that shapes regional landscapes and is vital for ecosystem functioning and human well-being. At the same time, water is a resource under considerable pressure. Alterations in the hydrologic regime due to global climatic, demographic, and economic changes have serious consequences for people and the environment.

As water scarcity increases and hydrological variability becomes larger, dealing with the changes brought by development presents a formidable challenge. The global water shortage narrative, combined with a recurrent discourse by international institutions emphasizing the role of water in the fight against unsustainable development, has put water issues at the top of many national and international agendas. Researchers and planners are challenged by the interlinked issues of water availability, water use efficiency, water productivity, and water allocation in order to ensure that human needs are met.

Water is essential for all socioeconomic development activities and for maintaining healthy ecosystems. As population increases, development calls for increased allocations of groundwater and surface water for the domestic, agriculture, and industrial sectors.

The need to adopt an integrated approach to the management of water resources is becoming a major concern throughout the world. The galloping rise in demand associated with increased water use and wastage is more serious because the available renewable resources are already overdeveloped. Pollution further exacerbates the water scarcity by contaminating surface and groundwater and reducing water usability downstream. As pressures on water converge on the region's water resources, the need for innovative approaches in water management becomes more apparent and quite urgent. The international community has recognized this fact, and over the past decade, a consensus had been formed on integrated water resources management (IWRM) as an appropriate approach to address the threats posed to water resources. Within the framework of sustainable management of water resources, IWRM takes into account a broad spectrum of social, economic, and ecological factors and their links. Effective coordination and participatory decision-making process are insured throughout IWRM. IWRM process depends on collaboration and partnerships at all levels, from individual citizens to international organizations, based on a political commitment to, and wider societal awareness of the need for water security and the sustainable management of water resources.

IWRM is an important development in water management and the best practice so far to help countries address the water-related challenges posed by economic and social development.

IWRM is a step-by-step process of managing water resources in a harmonious and environmentally sustainable way by gradually uniting stakeholders and involving them in planning and decision-making processes while accounting for evolving social demands due to such changes as population growth, rising demand for environmental conservation, changes in perspectives of the cultural and economic value of water, and climate change [44].

IWRM is a widely used concept in today's water literature and practice. One of the widely used definitions of IWRM is that of the global water partnership (GWP), which defines IWRM as follows: "IWRM is a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" [1].

IWRM helps to protect the world's environment, to foster economic growth and sustainable agricultural development, to promote democratic participation in governance, and to improve human health. Worldwide, water policy and management are beginning to reflect the fundamentally interconnected nature of hydrological resources, and IWRM is emerging as an accepted alternative to the sector-by-sector, top-down management style that has dominated in the past.

The basis of IWRM is that the many different uses of finite water resources are interdependent. High irrigation demands and the polluted drainage flows from agriculture mean less freshwater for drinking or industrial use; contaminated municipal and industrial wastewater pollutes rivers and threatens ecosystems; if water has to be left in a river to protect fisheries and ecosystems, less can be diverted to grow crops. There are plenty more examples of the basic theme that unregulated use of scarce water resources are wasteful and inherently unsustainable [9].

IWRM is a framework for the sustainable development and management of water resources for the whole society. IWRM plays a key role in social and economic development, particularly in sustainable development and poverty alleviation [14,36,39,43].

32.2 Sustainability

Sustainability is a vague concept, which is considered widely as a potential solution for many international, regional, and local problems facing society today, and has also been widely used in recent years for a wide variety of planning activities. The concept of sustainability, as it often appears today, attempts to reach beyond the environment/economy dichotomy, and embrace elements of the human social community. The efforts to expand the scope of sustainability can be characterized by briefly examining the types of reporting used to track sustainability in different communities [32].

32.2.1 Sustainable Development

The terms of sustainability and sustainable development are often used interchangeably in policy documents and in literature [17]. However, for the purposes of this chapter, the two phrases describe different phenomenon. Sustainability is best described as a state or a set of conditions that persist over time. A community may create a goal of achieving sustainability in a given period of time. Achieving sustainability would require the community to meet a series of conditions that define sustainability. These conditions for sustainability could include social equity, protection of the natural environment, minimal use of nonrenewable resources, economic vitality and diversity, community self-reliance, individual well-being, and satisfaction of basic human needs [17]. Sustainable development can be characterized as a pattern of social and structural economic transformations that optimize the economic and social benefits available in the present, without jeopardizing the likely potential for similar benefits in the future [13,26]. Sustainable development implies a process or series of incremental changes that move a community toward sustainability [17]. However, for a discussion of sustainability policy elements and sustainability indicators, the availability of different definitions is important. The potential exists for communities and organizations to provide policies that advocate for sustainability, but fail to provide the strategic steps to move toward sustainability, that is, a clear progression of development steps toward sustainability.

32.2.2 Water Sustainability

This chapter adopts the definition of "water sustainability" by which water resources and water services are able to satisfy the changing demand placed on them, now and into the future, without system degradation [16]. It also internalizes the 1992 Dublin Principles, arguably one of the most influential international statements about water and sustainable development. These principles are as follows [12]:

- *Principle 1*: Freshwater is a finite and vulnerable resource, essential to sustain life, development, and the environment.
- *Principle 2*: Water development and management should be based on a participatory approach, involving users, planners, and policy-makers at all levels.
- *Principle 3*: Women play a central part in the provision, management, and safeguarding of water.
- *Principle 4*: Water is a public good and has a social and economic value in all of its competing uses.

However, a more robust and actionable definition of water sustainability could be achieved by making a stronger link between water and sustainable development, as shown in these statements of key international agencies and declarations [7,22,35]:

- Combating poverty is the main challenge for achieving equitable and sustainable development, and water plays a vital role in relation to human health, livelihood, economic growth, as well as sustaining ecosystems.
- Water is a core cross-cutting element for reaching every other development goal. Access to water and sanitation is a prerequisite for ending poverty and hunger, achieving gender equality, and improving health and environmental sustainability, and should therefore be put higher on the agenda.
- Water is needed in all aspects of life. The general objective is to make certain that the adequate supplies of water of good quality are maintained for the entire population of this planet, while preserving the hydrological, biological, and chemical functions of ecosystems, adapting human activities within the capacity limits of nature and combating vectors of water-related diseases.
- The multisectoral nature of water resources development in the context of socioeconomic development must be recognized, as well as the multi-interest utilization of water resources for water supply and sanitation, agriculture, industry, urban development, hydropower generation, inland fisheries, transportation, recreation, low and flat lands management, and other activities.

Finally, GWP, a principal global advocate of water and sustainability, argues that sustainable development will not be achieved without a water-secure world, and provides more precise characteristics that further enlighten the concept of water and sustainability [4]:

- A water-secure world integrates a concern for the intrinsic value of water with a concern for its use for human survival and well-being.
- A water-secure world harnesses water's productive power and minimizes its destructive force. It is a world where every person has enough safe, affordable water to lead a clean, healthy, and productive life. It is a world where the communities are protected from floods, droughts, landslides, erosion, and waterborne diseases. Water security also means addressing environmental protection and the negative effects of poor management.
- A water-secure world means ending fragmented responsibility for water and integrating water resources management across all sectors—finance, planning, agriculture, energy, tourism, industry, education, and health. This integration is at the heart of the GWP's strategy.

- Achieving water security thus requires cooperation between different water users, and between those sharing river basins and aquifers, within a framework that allows for the protection of vital ecosystems from pollution and other threats.
- A water-secure world reduces poverty, advances education, and increases living standards. It is a world where there is an improved quality of life for all, especially for the most vulnerable—usually women and children—who benefit most from good water governance.

32.3 Water Scarcity

Rapid population growth, urbanization, high dependence on food imports, and the expansion of economic activities in many regions that are all exerting a huge pressure on scarce water resources [18].

There are several ways of defining water scarcity. In general, water scarcity is a relative concept and can occur at any level of supply or demand. Scarcity has various causes, most capable of being remedied or alleviated. A society facing water scarcity usually has options. However, scarcity often has its roots in water shortage, and it is in the arid and semiarid regions affected by droughts and wide climate variability, combined with high population growth and economic development, that the problems of water scarcity are most acute [41]. Symptoms of water scarcity include severe environmental degradation, declining groundwater levels, and increasing problems of water allocation where some groups win at the expense of others [42].

Water scarcity issues are becoming emergency issues and are going to play a key role in the near future for the definition of both environmental and development policies at a global scale. The term "water scarcity" has the following specific meanings [42]:

- An imbalance of supply and demand under prevailing institutional arrangements and/or prices
- An excess of demand over available supply
- A high rate of utilization compared to available supply, especially if the remaining supply potentials are difficult or costly to tap

The World Water Development Report defines water scarcity as [40]

> The point at which the aggregate impact of all users impinges on the supply or quality of water under prevailing institutional arrangements to the extent that the demand by all sectors, including the environment, cannot be satisfied fully, a relative concept that can occur at any level of supply or demand. Scarcity may be a social construct (a product of affluence, expectations and customary behavior) or the consequence of altered supply patterns stemming from climate change. Scarcity has various causes, most of which are capable of being remedied or alleviated.

The strengths of this definition include the recognition that water scarcity can occur at any level of supply and demand, that it has various causes, and that it is capable of being remedied or alleviated to a certain extent. The Comprehensive Assessment of Water Management in Agriculture states that water scarcity is a critical constraint to agriculture in many parts of the world [24].

The cause of water scarcity is of central concern when we want to determine under which conditions or through which measures scarcity can be combated and redressed. Molle and Mollinga (2003) distinguished between five types of constraints [26] (Table 32.1).

32.4 The Concept of IWRM

Although the concept of IWRM is highly challenged and criticized, it still remains the most popular and sound approach toward the sustainable management and development of water resources. Furthermore, it might be better to think of ways to support the implementation of IWRM principles and understandings and to create positive implementation practices, especially taking into account the idea that IWRM should not be seen as blueprint. It leaves room to search for case-specific ways to reach the desired goals of IWRM based on the appropriateness to the situation [15].

TABLE 32.1 Five Types of Constraints for Scarcity

Mode of Scarcity	Description
Physical scarcity	Corresponds to an absolute type of scarcity, where the water sources available are limited by nature. This is the common situation in arid and desert areas, where water sources are limited to only a few wells, springs, or Qantas.
Economic scarcity	Is the impossibility to cater to one of the described water needs or uses because of the incapacity to commit human resources (e.g., labor and time needed to procure water from very distant wells) or financial resources (e.g., payment for water) to access water.
Managerial scarcity	May occur because water systems are not properly maintained or managed: reservoir carryover stocks may not be considered, aquifers mined, irrigation schemes chaotic, water distribution networks leaking, etc. Improper management induces this scarcity, since users who should normally receive water fail to be served properly.
Institutional scarcity	Is a subtler dimension of induced scarcity, signifying a society's failure to deal with rising supply/demand imbalances and to preserve the environment. Water shortages can be partly ascribed to the inability to anticipate such imbalances and to supply adequate technological and institutional innovations. This may also include third-party impacts, that is, water problems experienced by some users because upstream patterns of land and water use change and impact on downstream access to water.
Political scarcity	Occurs in cases where people are barred from accessing an available source of water because they are in a situation of political subordination.

Source: Molden, D., *Water for Food, Water for Life*, International Water Management Institute (IWMI), Colombo, Sri Lanka, 2007 [25].

IWRM is a widely used concept in today's water management policy and practices. The concept is not new, but it was revived in the early 1990s when a number of internationally led policy processes, such as the Dublin International Conference on Water and Environment, started to promote IWRM as one of the key water management methods. A number of definitions of the concept exist, but perhaps the most widely used is that of the GWP, which emphasizes that the social, environmental, and economic aspects should be all developed hand-in-hand in a sustainable manner [8]:

> A process, which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.

The GWP noted that whereas certain principles underlying IWRM may be commonly applicable independent of context and stage of economic and social development, there is no universal blueprint as to how such principles can be brought into practice [8].

Bauer cautioned that it is evident that IWRM is an ideal concept rather than a set of specific guidelines and practices. Like "sustainable development," it is a phrase that can mean all things to all people; and because it seems to mean everything, it may end up meaning nothing [3].

Biswas similarly observed that a comprehensive and objective assessment of the recent writings of the individuals and institutions that are vigorously promoting IWRM reveals that not only no one has a clear idea as to what exactly this concept means in operational terms, but also their view of it in terms of what it actually means and involves varies very widely [4].

IWRM as presented by the GWP includes the integration of a variety of social, political, economic, and engineering/construction elements. Water management is just one aspect of a society, which also needs to manage a variety of other sectors (ideally in an integrated manner) such as energy, food supply, and transportation [8].

Perhaps IWRM should be considered an ideal toward which societies approach in a step-by-step manner, but one they will likely never fully reach, at least over a short to midrange (decadal) time.

Medema et al. (2008) observed that IWRM is not an end state to be achieved, it is a continuous process of balancing and making trade-offs between different goals and views in an informed way [22]. However, Biswas cautioned against this approach, noting that some have argued that IWRM is a journey, and not a destination, and the concept provides only a road map for the journey [4]. The problem with such reasoning, however, is that in the area of water management, we are long on road maps, but short on drivers.

Many areas of the world have water problems that need solutions now, and there is neither the time nor the resources to develop and implement an all-encompassing IWRM plan, assuming that it is practicably possible. Devising the IWRM principles and strategies is an interesting intellectual exercise, but the important matter is actually implementing plans that lead to more effective management of water resources. Medema et al. (2008) noted with respect to management frameworks in general that the community developing the framework (mostly academics) is unlikely to be the community that is actually implementing the framework [21].

Ideas may "appear good on paper," but may not be workable in the real world. Furthermore, the desire to develop a better long-term plan can become an excuse to not do anything now.

Mitchell (2008) raised a subtle but important issue in that there is a difference between a "comprehensive" approach and an "integrated" approach [24]. A comprehensive approach involves the consideration of all variables and relationships. However, an integrated approach involves examination of only the key variables and relationships that account for most of the variation in the system under consideration. Key variables may be identified based on existing data and knowledge, particularly local knowledge. An integrated approach may be more streamlined than a comprehensive approach.

The cross-sectoral integration between water use subsectors, and the role of IWRM in their linkage, is illustrated in the "GWP comb" in Figure 32.1 [9].

The IWRM framework and approach recognizes that the complementary elements of an effective water resources management system must be developed and strengthened concurrently. These complementary elements include (Figure 32.2) [9]

- *The enabling environment*, that is, the general framework of national policies, legislation, and regulations, and information for water resources management stakeholders.
- *The institutional roles* and functions of the various administrative levels and stakeholders.
- *The management instruments*, including operational instruments for effective regulation, monitoring and enforcement that enable the decision-makers to make informed choices between alternative actions. These choices need to be based on agreed policies, available resources, environmental impacts, and the social and economic consequences.

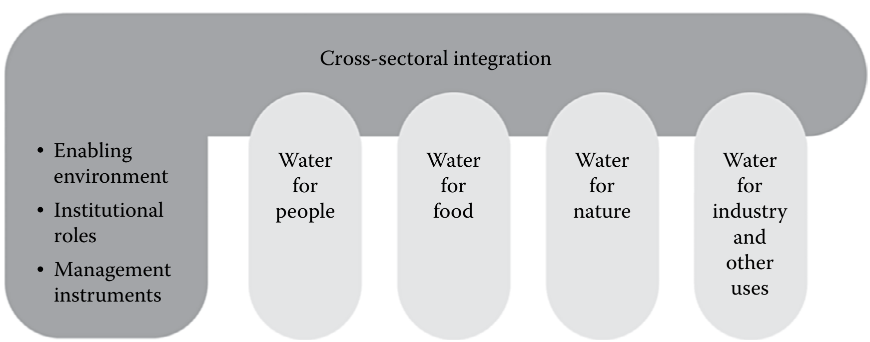

FIGURE 32.1 IWRM and its relations to subsectors.

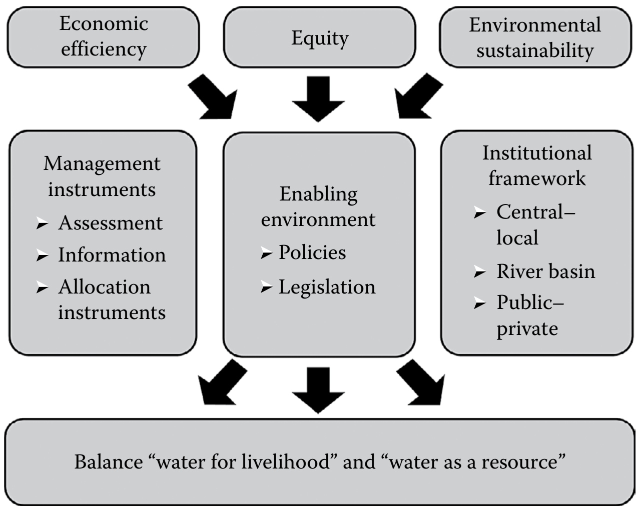

FIGURE 32.2 The three pillars of IWRM concept.

32.5 From Theory to Practice

The gap between the IWRM theory and practice has been identified as one of the major problems in IWRM by numerous authors (e.g., [22]).

Biswas claimed that IWRM has been used as a rhetoric by many, but few know what exactly is meant by the concept, and that opinions vary widely on what needs to be integrated and how [4]. Jeffrey and Gearey concluded similarly, stating that whereas IWRM as a concept promotes modern, holistic, and adaptive management approaches, the practice of water resources management is very

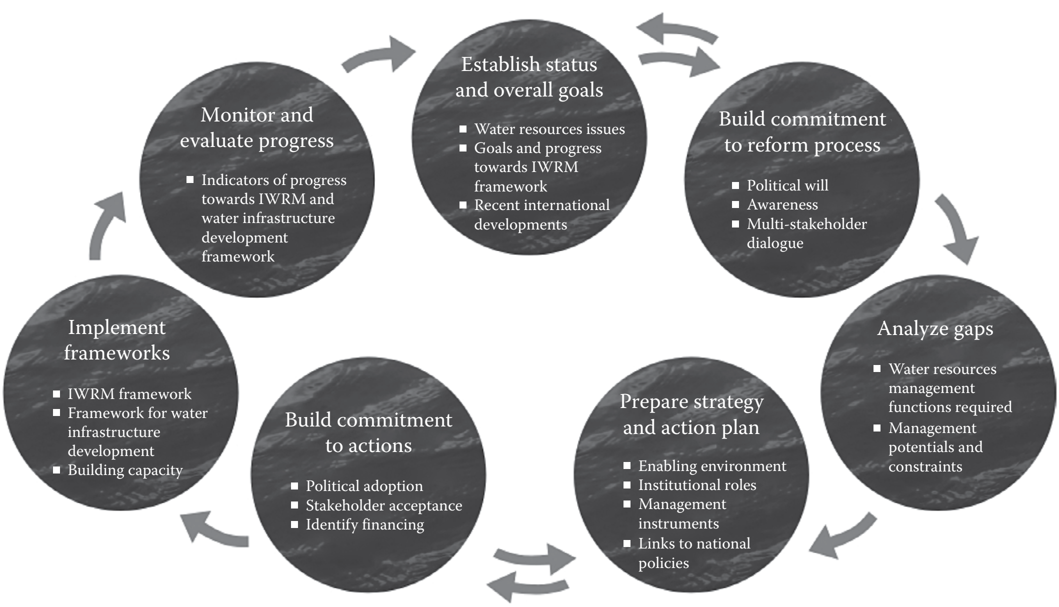

FIGURE 32.3 The IWRM planning cycle.

much driven by the contingency planning approach, and the "predict and prepare" paradigm [13]. Years of IWRM at the international policy level have not necessarily moved the concept toward more integration. For example, Rahaman and Varis analyzed thoroughly the Ministerial Declaration of the Fourth World Water Forum held in Mexico City in 2006, and concluded that it lacks many of the globally accepted water management principles [30]. Similarly, Biswas stated that the Mar del Plata Conference in 1977 concluded with more IWRM-related results than many of the international forums of the recent past [5].

Recently, a number of international organizations have geared their work toward translating the definition of IWRM into practice (e.g., [5]). UNESCO has produced the IWRM Guidelines at River Basin Level [11,16], which includes an introduction to a spiral model of IWRM in order to illustrate the evolving and dynamic characteristics of the IWRM process.

The key message of that model is that IWRM implementation can start immediately and evolve toward a fully integrated approach as capacity grows. The Global Water Partnership-International Network of Basin Organizations (GWP-INBO) in 2009 has produced the *Handbook for Integrated Water Resources Management in Basins*. The handbook emphasizes the creation of enabling institutional frameworks that promote the IWRM principles through policy guidance, legislation, and a well-functioning regulatory framework [38] (Figure 32.3).

32.6 Implementation

The implementation of IWRM remains insufficient in many cases. In addition to an inadequate institutional basis for governance and participation, it is often the lack of necessary competences that lead to unsustainable activities.

It has been recognized by many that there is a gap between theoretically agreed IWRM policies and actual implementation, which may stem in part from the ambiguity of the concept [5,13].

When there are the basic issues that need to be resolved, and many parties share responsibility, it is not clear who has the lead role, who should pay, and how such decisions are made [10]. Stakeholder participation in the decision-making process is inherently desirable, but how are decisions to be made when some of the parties involved have essentially irreconcilable economic interests?

Implementation of IWRM needs to be considered in the context of how real-world water management is performed. Those are the responsible for water management facing an existing complex of interrelated water, wastewater, social, economic, political, and environmental elements, that are often in conflict with each other. Actual water management decisions are typically made for a 1–5 year planning and budget period. Longer-term water management plans are often developed by water utilities and water management agencies, but usually it becomes outdated for the projects anticipated being constructed 10 years or more into the future and thus having little relevance.

Allan noted that IWRM is an intensely political process because water users have interests and do not want them to be diminished by such intervention [2]. A critical point is that there will be resistance to change, particularly by those who benefit by or are accustomed to the status quo. Allan also raised the important issue of there being a great schism in the acceptance of IWRM between developed countries (the North) and developing countries (the South). Knowledge of sustainability, IWRM, and water use efficiency are not readily assimilated by poor billions in the developing world, particularly when it contradicts deeply held beliefs and expectations about water [2]. Water users and communities must know about, understand, and want the new water management systems before they can be introduced and operated effectively.

From a practical perspective, the primary value of IWRM may be that it encourages a wider perspective and holistic view of water resources. An integral component of the applied IWRM is the consideration of a broad spectrum of options and applying systematic evaluation tools to the selection process [6].

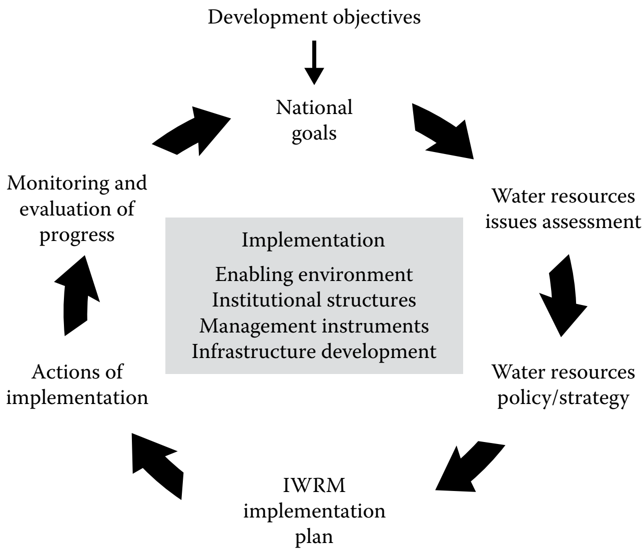

FIGURE 32.4 Worldwide progress in the development and implementation of IWRM.

A variety of strategies and technologies should be considered for increasing water supplies and making the existing use of water resources more efficient. The elements of IWRM that countries or communities may adopt include [19]

- Wastewater reuse
- Aquifer recharge
- Storm water management and flood control
- Storage (surface and underground)
- Demand management (conservation and reallocation)
- Conjunctive use of surface water and groundwater
- Development of alternative water supplies
- Water importation/exportation
- Virtual water trade

These elements are already being implemented throughout the world, but not necessarily under the banner of IWRM. It is the experience and observations of the authors that global water management is moving toward more integrated water management out of necessity. In large parts of the world, there are simply no more readily available additional freshwater resources and existing resources are under threat. Therefore, societies are being forced to make better use of existing resources or, if financial resources permit, developing new sources of water such as desalination. The changes are occurring largely within the existing social and political frameworks, with the rate of progress being controlled largely by economic resources and institutional inertia [19] (Figure 32.4).

32.7 IWRM Cross-Cutting Aspects

32.7.1 Capacity Development

The implementation of IWRM remains insufficient in many cases. In addition to an inadequate institutional basis for governance and participation, it is often the lack of necessary competences that lead to unsustainable activities. Existing knowledge concerning water must be continuously passed on, adapted, and extended. This involves, both, the people who use the water as well as the organizations and companies supplying it. In the end, the determining factors are the surrounding social conditions. Therefore, improvements in water management can only succeed as part of a multilevel campaign. In this respect, the capacities of individuals, institutions, and society as a whole to appraise, revise, and implement the available options are of vital importance.

The process of extending existing competence, strengthening skills, learning from experience, generating new knowledge and then identifying and addressing water-related problems can only be tackled in a comprehensive manner (UNDP [27]). The generic term for all these facets is capacity development (CD).

32.7.2 Decision-Making Support

In IWRM, planning processes are complex and many decisions need to be taken. The decision-makers are confronted with very varied and, in some cases, opposing usage requirements. So public planning decisions are not made spontaneously, but are the result of a long and thorough planning and decision process. From a practical point of view, this means that the first step is to gather together all of the information relevant to the decisions to be made and then analyzing it. On this basis, alternatives for the action are developed, the expertizes drafted and those who are affected are heard. The final step is to come to a balanced, comprehensive appraisal of the situation.

32.7.3 Governance

The term "governance" has to do with the question as to who shall make decisions about what, and according to which rules, in the management of water resources. A system of governance consists of a variety of parties (from government, nongovernment, and private agencies), institutions (e.g., formal and informal rules), and forms of interaction (e.g., of negotiating or hierarchical nature). Such a system is also affected by structures such as markets, hierarchies, and networks.

Governance plays an important role in IWRM, because it provides the political framework for its implementation. Such frameworks differ greatly from one country to another. There is a general agreement that the current global water crisis is caused less by the prevailing physical conditions than by poor governance. For this reason, the analysis and design of governance is of great importance to achieve the sustainable water management solutions.

32.7.4 Participation

Participation represents a vital building block toward successful implementation of IWRM as it stimulates comprehensive and trans-sectoral solutions. Participation has three essential functions. First, it is assumed that participation increases the actor's level of knowledge in respect to the sustainable use of water resources. Second, participation can help to balance varying interests in that those involved in the process come to see other points of view, and this in turn forms a basis for intersectoral or cross-border cooperation. Third, participation has a beneficial effect on the degree of acceptance and ownership of the decisions made. Thus, the participatory process often proves to be a necessary condition for making decisions transparent and acceptable. Here, participation is to be understood as the involvement of people who are affected by an issue, but are not routinely involved in political decision-making processes. Those affected may be members of the general public or individual representatives of various water-related sectors, politicians or administrators at local levels.

32.8 Guidelines to Successfully Implement IWRM

Rahaman and Varis highlighted seven points and approaches that need to be addressed by water professionals far more carefully than in the contemporary guidelines to successfully implement IWRM [30].

32.8.1 Privatization

Privatization of the marketable aspects of water may result in single-purpose planning and management, which raises a question of open information channels and transparency. Moreover, for the developing world where basic infrastructure is not yet complete, the question remains of whether applying full cost recovery is ethical or practical. Water resource management by public or government organizations also has many success stories. It is important that IWRM not only deals with water supply and wastewater treatment, but it combines many other functions, including flood control, poverty alleviation, food production, ecosystem conservation, drought management, and sustainability, and that the government's presence is vital in the effective implementation of IWRM.

32.8.2 Water as Economic Goods

Water is recognized as economic goods in many international declarations, such as those reviewed earlier, as well as in the policies of major lenders and donors. However, there is a risk in fostering the notion of water as a commodity, because it shifts the public perception away from a sense of water as a common good, and from a shared duty and responsibility. The application of economic principles to the allocation of water is acceptable, and provides a simple tool for the development of water services in a more efficient direction. A simple and straightforward solution, designed on the basis of pure economic efficiency, has the potential of ending up unsustainable.

32.8.3 Transboundary River Basin Management

Water should be recognized as a tool for community development, peace building, and preventive diplomacy. Water can have an overreaching value capable of coalescing conflicting interests and facilitating consensus building among societies. To incorporate all of the physical, political, and economic characteristics for a river basin, a process for cooperative watershed management is vital. For this reason, water should be managed based on river basins, in addition to administrative boundaries. Existing river basin commissions all over the world are facing the difficulties to enforce the basin plan provisions in other sectors in addition to riparian governments. Other challenges include the lack of effective local participation, the absence of formal agreements on international water allocations, the limits on pollution, and the economic and military power imbalance between upstream and downstream countries. In addition, a greater focus on legal institutional arrangements is necessary, as it is practically absurd to implement integrated policy without some legal bindings. A common policy, including a supporting legal framework, is vital for implementing integrated transboundary river basin management.

32.8.4 Restoration and Ecology

In the last three decades, the highly visible effects of environmental degradation have sparked public outcry. Channelization, together with a myriad of other activities, such as construction, land-use change, urbanization, and waste disposal, creates a wide range of biological impacts, principally on benthic invertebrates, fish, and aquatic vegetation. In addition, due to the lowering of water tables in adjacent floodplains, natural vegetation and wildlife are also threatened. As a consequence, riverine floodplains are among the most endangered landscapes worldwide [28]. The IWRM principles do not clearly focus on or address the mechanism of river restoration, which is necessary for the sustainable water resources management in areas that have undergone or are presently subjected to notable modifications.

32.8.5 Fisheries and Aquaculture

Fisheries and aquaculture are crucial for human survival and poverty reduction; they provide an inexpensive source of protein to meet nutritional demands in many parts of the world, and therefore should command special attention within IWRM. Unfortunately, fisheries are generally undervalued in terms of their contribution to food security, income generation, and ecosystem functioning. Aquaculture is the most rapidly growing industry when looking at protein production for human consumption. Although aquaculture and coastal and marine fisheries do not directly rely on freshwater, the input of nutrient and sediment from inland streams, particularly into estuaries and coastal zones, results in interplay between marine and inland water ecosystems, which is not addressed sufficiently in the present IWRM debate. The same goes for fisheries.

32.8.6 Need to Focus on Past IWRM Experience (Integrating Lessons Learned)

Although IWRM has received increasing international attention in recent decades, historical precedents present lessons. The current IWRM mechanisms have not properly considered similar previous attempts. Lessons from past initiatives are vital to the implementation of IWRM principles and policies. One of many implementations was the countrywide construction of municipal wastewater treatment plants, which at that time were already more advanced than current plants in many countries that promote IWRM worldwide. Unfortunately, the current IWRM mechanism does not focus on this kind of highly balanced experience in integrated plans, which would facilitate more concrete IWRM development.

32.8.7 Spiritual and Cultural Aspects of Water

Water is the common symbol of humanity, social equity, and justice. It is one of our compelling links with the sacred, with nature, and with our cultural heritage. Regrettably, the current IWRM mechanism does not acknowledge water's spiritual and cultural dimensions. Without recognizing these, it is possible that all efforts toward sustainable water resources management may be piecemeal and ephemeral.

32.9 Future Challenges of IWRM

A relatively recent survey by the GWP reveals that only 20 out of 95 countries surveyed had implemented IWRM at the policy level [20]. A more recent undertaking showed that this percentage had grown to the point that 65% of countries presented some degree of IWRM implementation by 2012. However, the same report mentions that it had slowed down or regressed in countries with a low or medium human development index since 2008 [40].

The international community now recognizes IWRM as the most efficient and effective water resources management mechanism to enhance economic well-being, social equity, and environmental sustainability. In practice, though, implementation of the IWRM concept is challenging. The integration of different sectors related to water management is a difficult and challenging task. Moreover, the problems and solutions associated with the IWRM implementation in different regions are not universal. Overly general or universal policies and guidelines for implementing IWRM may become counterproductive [31].

Understanding the challenges and their interconnections is a critical step in effective policy design, policy implementation, and consensus building. IWRM provides a lens through which the many interlinked drivers and potential consequences of economic, social, and environmental changes can be identified and coordinated actions formulated to holistically achieve economic efficiency, social equity, and environmental sustainability based on publicly available and transparent information. Its implementation in the new context will need categorizing to optimize spin-offs and plans of action for the short, medium, and long term. It requires [15]

- Policy instruments that promote complementarities (economic, social, and environmental) and leverage change
- Fiscal instruments that give a price to environmental goods
- Strengthened institutional arrangements that function within increasing complexity, cutting across sectoral silos and sovereign boundaries

- A new generation of financial instruments that share the risk between governments and investors and make new technology affordable
- Skills development that supports the emerging green sectors in the economy
- Transparent information and monitoring: set targets, define trajectories, and gather the right information to monitor progress (e.g., on water/energy efficiencies)
- Education and awareness raising

The concept of IWRM is anticipated to make a vital contribution toward meeting the challenges ahead. It was established as early as 1992 as an international guiding principle within the framework of the Dublin Principles and Agenda 21. This concept is based on the sustainable quantitative and qualitative management of the interacting components, surface waters, aquifers, and coastal waters, in order to not only support social and economic development but also to preserve ecosystem functions. Ecological, economic, and social objectives must be linked together. This means the active participation and cooperation of different social and private stakeholders (Figure 32.4). IWRM has already advanced to become a guiding principle in water management, and it has spawned many technical and conceptional innovations. It is the visible evidence of a paradigm shift from sectoral thinking toward integrated concepts. Enormous progress has been made during recent years in the development of integrated management plans, but their implementation is lagging behind. According to a United Nations survey, 65% of 133 countries have developed IWRM plans, while only 34% report an advanced stage of implementation [37].

32.10 Case Study

The United Nations reported several case studies with on-site implementations of IWRM [11]. These include the examples from places as diverse as Malaysia, Chile, the United States, and China. Rogers and Leal also presented a series of case studies, which could loosely fall under the umbrella of IWRM [32].

This study applies the concept of IWRM to a river basin in Iran, and in so doing, proposes a framework for implementing the IWRM principles. Issues such as stakeholder participation, sustainability in several subdomains, scenario analysis, dispute resolution, climate change, and well-designed models have been considered [45]. Through a river basin simulation model (RIBASIM) and sustainability criteria, stakeholders made decisions for improving the level of sustainability in the basin. The results of decision-making for the future were tested under climate change impacts, and the outputs showed serious challenges, so a strategy is proposed for overcoming these impact effects.

32.10.1 Methodology

In this study, a generalized framework and comprehensive river basin simulation model were used to define and evaluate the alternative management policies for sustainable development of the entire basin. This system is designed to inform the decision-making process. The approach includes scenario development, river basin simulation, climate change impact assessment and adaptation, stakeholder participation, dispute management, and group decision-making (Figure 32.5).

The planning and analysis approach included four main segments: (1) river basin simulation and scenario definition, (2) definition of criteria and their limitations and forces, (3) decision-making and participation, and (4) climate change impact assessment and adaptation [46]. The first segment focused on river basin simulation of the study area and scenario development. The second concerned sustainability development and the associated relationship with water resource management and the IWRM principles. The third part is characterized as an approach to make decision and to negotiate and dispute the solution in the water resource management structure for the study area. It also dealt with the stakeholder participation through verbal statements. From the third part of the framework, the best scenario for short-term management and the best strategy and scenario for long-term planning were chosen. In the last segment, the selected strategy for long-term planning was assessed for climate change impacts and the adaptation strategy for overcoming adverse impacts was introduced.

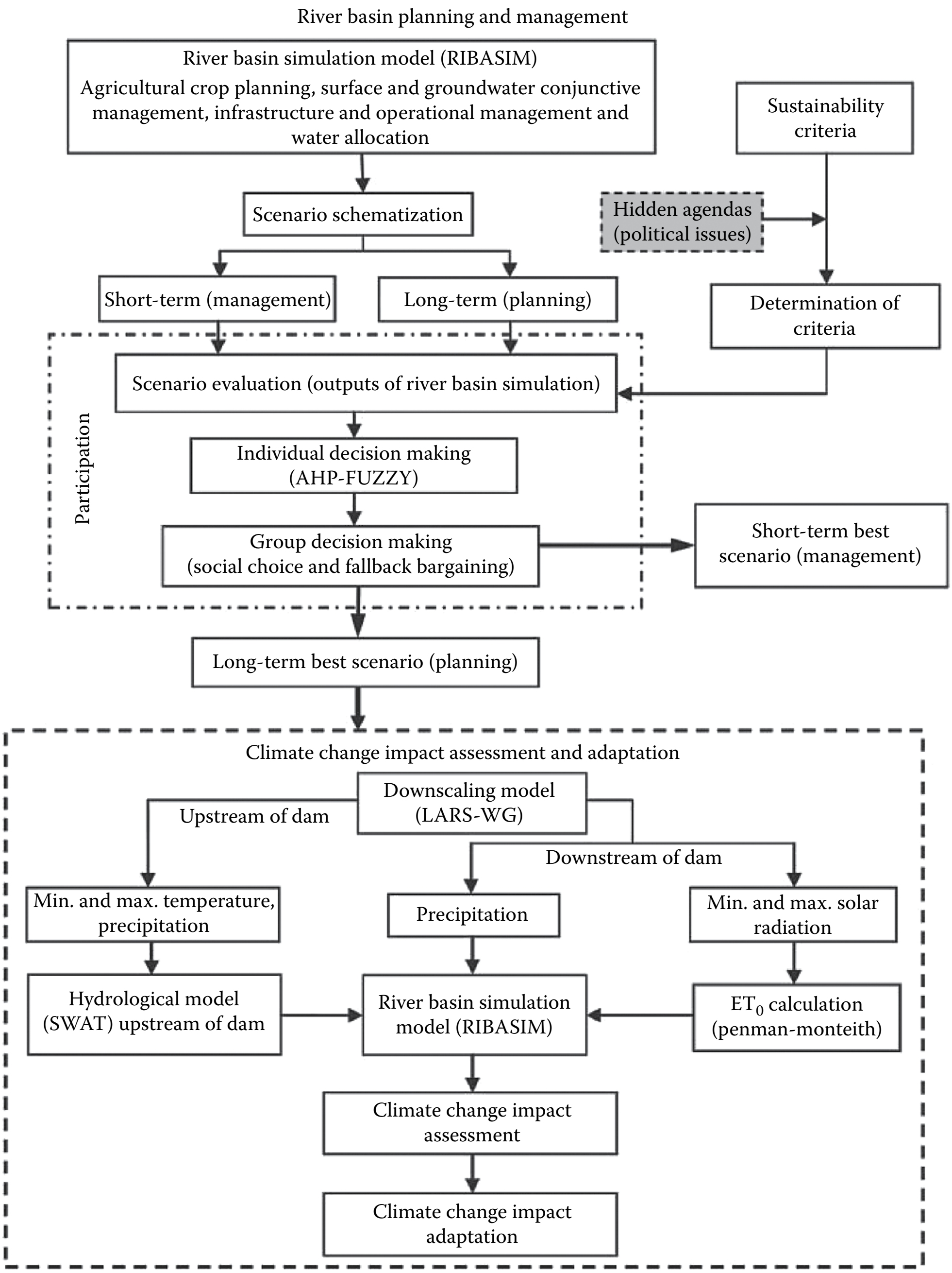

FIGURE 32.5 River basin planning and management framework.

32.10.2 Study Area

The Zayandehrud River basin covers about 26,917 km² of mostly arid land, yet it supplies the water requirements of many cities and villages in the central Iran. This area is also important because of its substantial industrial development and tourism and water supply projects for two big cities, Yazd and Kashan [29]. Continuous declination in the quality and quantity of groundwater resources has caused an irreparable environmental damage to the river and Gavkhuni Wetland ecosystems [33]. Water shortages in the basin often result in the needs of stakeholders, especially farmers, not being met. Also, this basin is witnessing uncontrollable development in agriculture, industry, and urban areas. The stresses caused by water deficits constrain sustainable development in economic, social, and environmental aspects and create disputes among different stakeholders. To prevent further damage to the natural and social environments and administration of justice in the allocation of water, the Zayandehrud River basin needs a comprehensive plan. Applying IWRM in this basin is proposed as a way to meet these challenges.

32.10.3 Results and Discussions

In this chapter, theoretical concepts of IWRM in practice and in a complex basin are implemented. The design steps in this research are general and could apply to other case studies as a framework for decision-support systems. The most important issue in this approach is stakeholder participation, because decision-making without consideration of stakeholders' opinions is not practicable. So, in this study, reaching a group decision from the lowest possible level and balance of powers, and also awareness of the stakeholders and decision-makers of the consequences of their policies, have been intended. They made decisions through scenario analysis by using the criteria that play an important role in the sustainability of the basin. Through these criteria and using excellent modeling and simulation, efficient scenario analysis, and decision-making methods, the best option can be selected with the aim of improving sustainability.

The results of the study of the Zayandehrud River basin in drought years show that environmental issues in drought periods are essential in sustainability development; agricultural demand has less importance in water allocation. But in normal and wet years, because more water is available for users, environmental issues are supplied efficiently and the industry demand has a higher priority in water allocation than agricultural and environmental demands. The decision-making results for normal and wet years are similar to the current facts of basin management, perhaps because of the several decades of experiments in the basin's management and lower conflicts, shortages, and damages during these years. But in drought years, the selected scenario and the reality of management in the basin are very different, and regional policies have led to vulnerability and damage to the basin's sustainability, especially in its environmental and ecological aspects. Hence, the new selected option can be applicable in reducing the damage to sustainable use of water resources, especially with increasing the priority of environmental issues in water allocation.

This policy was selected due to the high importance of environmental and ecological issues in stakeholder opinions and the lower amount of water demand of these users compared to other users such as industry and agriculture. With this pattern, the basin would face fewer challenges in the short and the long term. Also, the importance of the industrial sector is considerably more than the agriculture sector, specifically in view of economic, social, and political matters. The best scenarios can bring about sustainable development in the basin. In the long term, according to the methods of dispute resolution, scenario with supply orientation has been selected as the best scenario for planning strategy in future; the inter-basin water transfer approach scenario (changes in cropping pattern) was rated only a little lower. Undoubtedly, this plan could lead to increasing the capacity of the basin for developing policies and controlling stresses and shortages compared to continuing the current approach of supply and demand management [34].

Also, it is a unanimous decision that demonstrates the positive effects in improving the sustainability of development of the basin and reducing conflicts. But this planning strategy must be assessed for climate change impacts in future. In the assessment of climate change impacts, it is observed that climate change can be a major risk for sustainable development. The selected plans for the basin in the future and the water resources of this basin will be faced with major vulnerability, so the basin system needs to adapt to these impacts. The solution presented in this study is a demand-oriented policy, with changes in cropping patterns along with the supply approach in planning for the future. The conclusion of this policy shows a fundamental reduction in the basin's vulnerability to climate change impacts through reducing agricultural water demand (a major water usage in the basin) and improving the balance between supply and demand.

The approach presented here is distinguished by its close approximation to the reality of the decision-making process in water resources management, while considering essential factors of an IWRM framework. This allows computer models to better approximate actual decision-making.

With respect to IWRM, Mays noted that it is usually impossible to have a completely integrated urban water management system, but considerable potential exists for improving urban water management through a better "integrated" consideration of the various aspects and options [21]. Progress may be slow and questions complex but there really is no alternative to IWRM [35].

32.11 Summary and Conclusions

A risk of creating excessive, unrealistic expectations concerning what can be achieved through IWRM is that it can lead to disillusionment or frustration and abandonment of the entire concept. However, adopting an integrated approach may be successful for smaller-scale, better-defined problems, particularly, when there is consensus that such an approach is needed and a clear, specific objective has been developed.

Few would argue against the concept that water should be managed in a more holistic and comprehensive manner and that all stakeholders should be able to participate in its management to some degree. The core of IWRM is in fact only an elaboration of what should be considered good water management and sound decision-making. Although, many criticisms of IWRM concerning its ambiguity, lack of objective evaluation criteria, and difficulty of implementation are valid. Perhaps the greatest value of IWRM is that it may encourage some societies to adopt more effective water management schemes by viewing water issues in a broader context and considering more options.

Managing water resources now means meeting both human and ecosystem needs. It is clear that IWRM requires fundamental changes in values, beliefs, perceptions, and political positions, not only in water management institutions but also in the stakeholders themselves.

Water is prevalent in all aspects of human life, from domestic use to economic activities and ecosystem conservation. IWRM is a welcome addition to the water management community in the sense that it provides a much-needed framework to deal with all these aspects in a joint manner. For all its shortcomings, however, IWRM is best described as a useful utopia that prompts water managers and users to think of the broader picture, thus raising awareness about the manifold nature of the resource and making its use more sustainable.

Perhaps the greatest challenge in modern water management consists in the need to integrate tangible realities: volumes of consumptive and nonconsumptive water use, pollutant concentrations, economic figures and related jobs along supply chains; and intangible values: cultural, religious, political, educational, and others.

The former provides a necessary foothold on objective figures, while the latter are difficult to manage and quantify but usually play a larger role in political decisions. Since all contexts are different, there can be no universal blueprint to underpin water policy. In this sense, tailor-made assessments based on strong public participation processes are advocated as a means to optimize water management at the basin scale.

Another important challenge pertaining to water management is the fact that many of the decisions that affect water are made outside of the formal planning process. These include key issues such as trade, agriculture, energy, and economic or environmental policy, and can be made by actors as diverse as individual farmers, international corporations, or supranational authorities. In this regard, relatively new paradigms like corporate social responsibility or virtual water call for further consideration within the water management process.

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33

Drought and Dust Management

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Abstract A dust storm is a meteorological phenomenon common in arid and semiarid regions. Dust storms arise when a gust front or other strong wind blows loose sand and dirt from a dry surface. Particles are transported by saltation and suspension, a process that moves soil from one place and deposits it in another. Drylands around North Africa and the Arabian Peninsula are the main terrestrial sources of airborne dust, in addition to some contributions from Iran, Pakistan, and India into the Arabian Sea, and China's significant storms deposit dust in the Pacific. It has been argued that, recently, poor management of the Earth's drylands, such as neglecting the fallow system, is increasing dust storms' size and frequency from desert margins and changing both the local and the global climate, besides impacting local economies. In desert areas, dust and sand storms are most commonly

caused by either thunderstorm outflows or strong pressure gradients, which cause an increase in wind velocity over a wide area. The vertical extent of the dust or sand that is raised is largely determined by the stability of the atmosphere above the ground as well as by the weight of the particulates. In some cases, dust and sand may be confined to a relatively shallow layer by a low-lying temperature inversion. In other instances, dust (but not sand) may be lifted as high as 20,000 ft (6,100 m). Drought and wind contribute to the emergence of dust storms, as do poor farming and grazing practices by exposing the dust and sand to the wind.

33.1 Introduction

Drought has increasingly intensified in recent years globally due to climate change and desertification and has significantly contributed to the increase in dust. Due to desertification, which results in dried soil, smaller particles sizes have been increasing in the air, which are then converted into the form of aerosol; thereby, by wind currents or other physical processes, they join the two airflows. Very small particles are known as dust [44]. Dust particles contain aerosols (clay and silt). These can be transmitted over long distances and to high altitudes in the atmosphere and ultimately could be deposited in dry or wet form [30].

Sand and dust storms are natural events that occur widely around the world in arid and semiarid regions, especially in subtropical latitudes [44]. The vast distribution and existence of desert landscapes (Figure 33.1) indicate that these regions were a very important source of dust storms in historical times, but in more recent times the action of humans has created another source on the desert margins in semiarid areas that previously used to be stable. Major dust storms occur where anthropogenic land disturbances exist in drylands under severe drought. Several areas of the world are contributing to large-scale storms. These areas correspond to areas undergoing accelerated desertification.

North Africa is a source of dust for Southern European dust deposition [51]. Similarly, the Sahara region is the main source of Aeolian dust in the world [33]. Dust is transported westward over the Atlantic Ocean and Sahara region and northward over several cycles of transport and deposition. Pease et al. suggested that arid and semiarid regions around the Arabian Sea are one of the principal sources of global dust. India, Pakistan, Iran, and the Arabian Peninsula contribute to the Oman Sea dust deposition (Figure 33.2) [39].

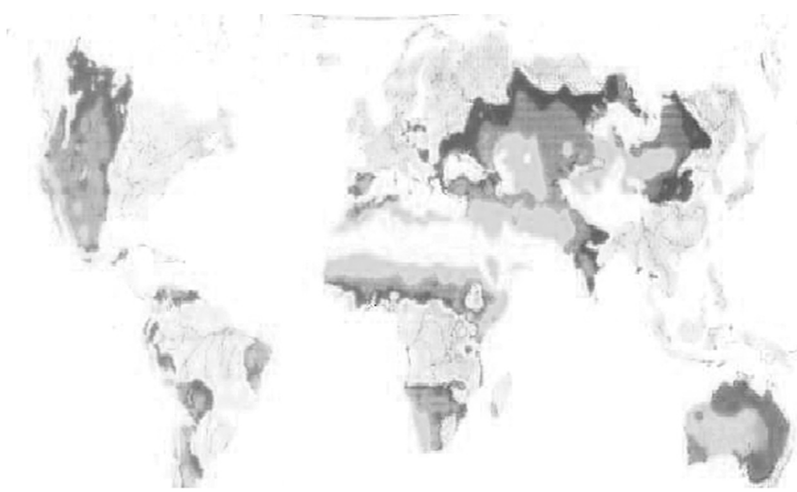

FIGURE 33.1 Vast distribution and existence of desert landscapes.

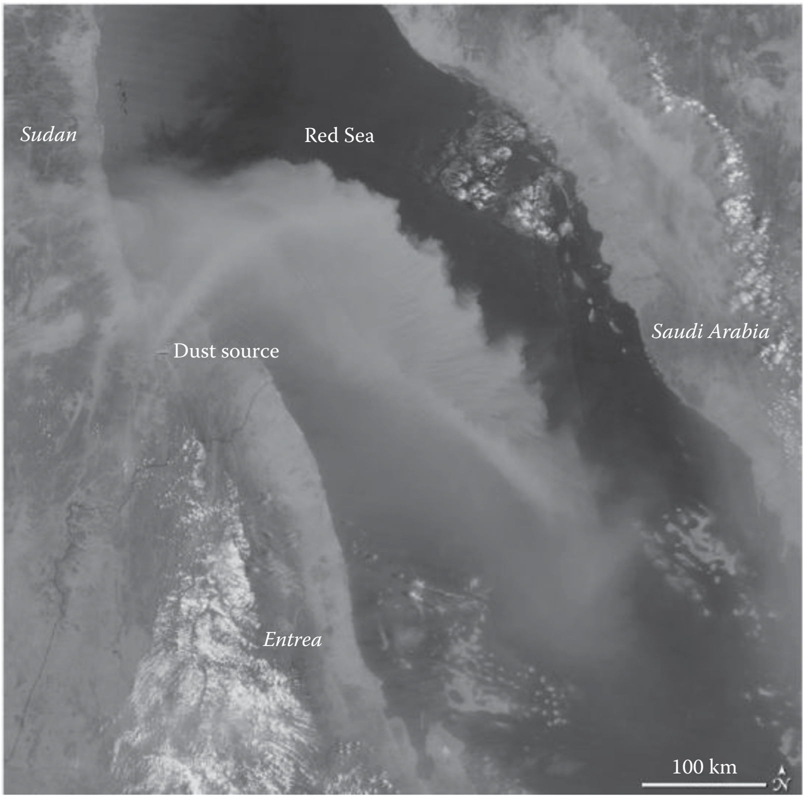

FIGURE 33.2 Satellite image of dust over the Red Sea; Saudi Arabia is located in the right-hand side of the image.

33.2 Sand and Dust Storms: Terminology and Physical Process

Conventionally, “sand” describes soil particles of an approximate size range of 0.6–1 mm, while “dust” describes particles <0.6 mm. In practice, only those dust particles below 0.1 mm can be carried by suspension and be manifested in a dust storm. Thus, dust storms are a product of mass transportation of soil particles by wind. Dust storms are typically a form of dry deposition. Often, the fine fraction that is richer in nutrients and organic matter is entrained into the air, upon which dust particles become condensation nuclei. These small particles may be deposited subsequently as a wet deposition through rain or snow.

The transport, suspension, and deposition of dust particles in the atmosphere mainly manifest as a dust storm. Major storms occur when prolonged drought causes the soil surface to lose moisture and there is a co-occurrence of strong winds.

Field observations and wind tunnel laboratory research allow us to understand the physical process. Consider a surface made up of separate particles that are held in place by their own weight and some interparticle bonding. At a low-speed wind, there will be no indication of motion, but when the wind force reaches the threshold value, a number of particles will begin to vibrate. Increasing the wind speed still further, a number of particles will be ejected from the surface into the airflow. When these injected particles impact back on the surface, more particles are ejected, thus starting a chain reaction. Once ejected, these particles move in one of three modes of transport depending on particle size, shape, and density. These three modes are suspension, saltation, and creep. The size and density determine the movement pattern of sand/dust particles (Table 33.1).

TABLE 33.1 Movement of Soil Particles under a Wind Force of 15 m/s

Particle Size (mm)	Period of Suspension (Time)	Comment/Description
0.1	0.3–3.0 s	Fine sand
0.01	0.83–8.3 s	Dust; can go up to 700 m high
0.001	0.95–9.5 years	Fine clay; can go up to 77 km high

The suspension mode involves dust particles of less than 0.1 mm in diameter and clay particles of 0.002 mm in diameter, both of which are small in size and light in density. These fine dust particles may be transported at altitudes of up to 6 km and move over distances of up to 6000 km. These red-colored and alkalized dust particles are 0.1 mm in diameter and suspended high in the atmosphere and contribute to a general loss of visibility, but do not manifest as a real dust storm. The research results of the Geology Faculty of Oxford University in the United Kingdom show that Great Britain has suffered dust storm disasters 17 times since 1900. About 10 million tons of dust particles is transported and brought to Great Britain from the Sahara Desert during a single dust storm.

Satiating particles (i.e., those between 0.01 and 0.5 mm in diameter) leave the surface, but are too large to be suspended. The remaining particles (i.e., above 0.5 mm) are transported in the creep mode. These particles are too large to be ejected from the surface and are therefore rolled along by the wind and impacting particles. Coarse sands of 0.5–1.0 mm in diameter move along in a rolling movement. Medium-sized sands of 0.25–0.5 mm in diameter encroach in the form of a jumping movement. As these particles impact upon the land surface, they initiate movement of other particles. About 50%–80% of all soil being transported is carried in this mode. Due to the nature of this mode, the heights carried are rarely more than 30 cm and the distances traveled rarely exceed a few meters.

Sand particles, transported by saltation and by creep, accumulate to form new sand dunes when they are blown out, graded, and transported for a distance (Figure 33.3). Sands of 2.0 mm in diameter will be left on the land surface when fine materials are blown away (Figure 33.4).

FIGURE 33.3 Sand and small gravel remains after finer particles, including organic matter, have been blown away. This wind is constantly moving the sediments, leaving a typical windswept surface.

FIGURE 33.4 Sand dunes form when sand is moved along by the wind (see text).

33.3 Interaction between Climate, Water, and Dust Storms

The identification of the factors contributing to dust storms is a complex process, since the factors pointed out as the main originators of land degradation are the most varied, such as climate change, deforestation, predatory exploitation, extensive cultivation, industrialization, and urbanization [43]. Indeed, there are many factors that trigger dust storms, including the unpredictable effects of drought, fragile soils and geological erosion, livestock pressures, nutrient mining, population increase, landlessness and an inequitable distribution of resources, poor infrastructure and market access, neglect by policy-makers and agricultural and environmental research systems, as well as the failure of markets to reward the supply of environmental services.

Climate and desertification interact at a variety of scales. Indeed, climate affects the desertification processes through its impact on dryland soils and vegetation, as well as on the hydrological cycle in drylands [20]. Unlike the organically rich soils of more humid regions, dryland soils often have low organic matter content and are frequently saline and/or alkaline. Moreover, desertification affects global climate change through soil and vegetation losses. Specifically, dryland soils contain a lot of carbon, which could be released into the atmosphere as a result of desertification, with significant consequences for the global climate system. Indeed, the effect of global climate change on desertification is complex and not yet sufficiently understood. At first, higher temperatures can have a negative impact through increased loss of water from soil and reduced rainfall in drylands. On the other hand, an increase in carbon dioxide in the atmosphere can boost plant growth for certain species.

33.3.1 Aridity Classification

Although climate change may increase aridity and desertification risk in many areas, the consequent effects of biodiversity loss on desertification are difficult to predict [49]. Moreover, arid, semiarid, and dry subhumid areas, other than polar and subpolar regions, are defined as the areas with a 0.03–0.65 ratio of annual precipitation (P) to potential evapotranspiration (PET), which is known as the Aridity Index (Table 33.2).

TABLE 33.2 Dryland Categories

Aridity Index: Precipitation/Potential Evapotranspiration (P/PET) PET > P	Rainfall (mm)	Classification of Desert Climate
<0.03	<200	Hyperarid
0.03 to <0.20	<200 (winter) <400 (summer)	Arid
0.20 to <0.50	200–500 (winter) 400–600 (summer)	Semiarid
0.50 to <0.65	500–700 (winter)	Dry subhumid
>0.65	600–800 (summer)	No desertification

In general, when the ratio is lower than 0.03, there is always desertification, whereas when the ratio is higher than 0.65, there is no desertification.

One important aspect is the difference between aridity and drought, as stated [8]: "Aridity implies a high probability of rainfall for a given period below a low threshold. Drought implies a low probability of rainfall for a given period below a relatively low threshold." This statement implies that aridity is considered as a long-term climatic characteristic of a region, whereas drought is a short-term climatic feature with increasing periodicity and frequency of occurrence.

33.3.2 Drought Concepts

Reference has already been made to the role of prolonged drought in exacerbating the severity and frequency of dust storms. This is due to several causes. The most obvious are reduction in plant cover and drying of the soil. Bare, dry soil is more susceptible to the actions of the wind. Plant cover reduces wind velocity at the soil surface and moisture improves cohesion between individual soil particles. However, the major effect of prolonged drought seems to be to force land users to take greater risk and impose greater pressure on an already stressed environment.

Drought is part of nature's climate variability. Indeed, drought is considered as a natural regional phenomenon with a temporal periodicity. Essentially, droughts originate from a deficiency or lack of precipitation in a region over an extended period of time. This is why droughts are also referred to as "nonevents" and can be considered as extreme climatic events associated with water resources deficit. Moreover, drought is considered as one of the major natural hazards with significant impacts on several sectors of the economy, society, and environment [46]. There are several unique characteristics that differentiate drought from other environmental hazards, namely, its slow onset, often characterized as a creeping phenomenon; its nonstructural impacts, which can be regional or local, lasting for a long or a very short time; as well as the absence of a universal definition, leading to inaction [32,52]. Moreover, the impacts of droughts may be severe and are neither immediate nor easily measured. All the above may accumulate difficulties in drought assessment and response, which may result in slow progress on drought preparedness plans and mitigation actions.

There is a need to establish the context in which the drought phenomenon and its associated impacts are described, leading to a better definition. If drought is considered as a phenomenon, it is certainly an atmospheric phenomenon. However, by considering drought as a hazard, there is a tendency to define and classify it into different types. Definitions of drought help in identifying its duration and severity and are useful in recognizing and planning for it [10,11]. Four operational definitions are commonly used, namely, meteorological or climatological, agricultural or agrometeorological, hydrological, and socioeconomic drought [24,31]. With the exception of meteorological drought, the other types of drought emphasize on the human or social aspects of drought, in terms of the interaction between the natural characteristics of meteorological drought and the human activities that depend on precipitation [12,13]. As their names imply, these diverse drought types impact different sectors, but in most instances, the impacts related to each sector overlap both temporally and spatially. Drought concepts refer to conditions of precipitation deficit, soil moisture, streamflow, plant wilting, wild fires, famine, as well as other components. Indeed, drought is a multifaceted issue and drought quantification requires a multifaceted assessment. Moreover, drought monitoring involves climate data; soil moisture; streamflow; groundwater, reservoir, and lake levels; snowpack; short-, medium-, and long-range forecasts; as well as vegetation health/stress and fire danger.

There is a medium confidence that droughts are expected to intensify in the twenty-first century in seasons and areas due to increased evapotranspiration and/or reduced precipitation. These areas include Southern Europe and the whole Mediterranean, Central Europe, Central North America, Central America and Mexico, Northeast Brazil, and South Africa [29]. As already mentioned, all droughts begin with a deficiency of precipitation in a region over a period of time. These early stages of accumulated departure of precipitation from normal or expected are usually considered as meteorological drought [45]. Thus, a meteorological drought in terms of lack of precipitation is the primary cause of a drought. A continuation of these dry conditions over a longer period of time, sometimes in association with above-normal temperatures, high winds, and low relative humidity, quickly results in impacts on agricultural and hydrological sectors. Indeed, this usually first leads to an agricultural drought due to lack of soil water. If precipitation deficiencies continue, a hydrological drought in terms of surface water deficits develops. The groundwater is usually the last to be affected, but also the last to return to normal water levels. Meteorological droughts are characterized by a change in the local meteorological conditions, such as the prevailing of a high-pressure ridge. The geomorphological and climatological characteristics of a region play an important role in meteorological drought, since they may imply different precipitation regimes. Meteorological droughts can develop quickly, but they can also end just as quickly if the precipitation deficits are relatively small. However, these types of drought may also develop into a multiseasonal event, leading to one of the other types of drought.

In general, drought is defined by meteorologists as a period of rainfall in the lowest decile [22]. This means that droughts occur in all climatic regions with the same frequency, that is, 10% of the time. This definition says little about the severity or duration of the drought. If droughts are perceived to occur more frequently than 10% of the time, then it is because land management is inappropriate for climatic variability, so the land is under stress in periods with rainfall well above the tenth decile; that is, management is inappropriate for normal climatic variability. It is not the climate that is at fault, but human perception of the land as being better than it is.

Weather refers to the environmental conditions being experienced on a day-to-day (even hour-by-hour) basis, but climate is the pattern of these occurrences over a long time period. Weather can be conducive to the advent of dust storms on some days or at certain times of a given day.

Many people associate desertification with droughts. While it is true that land degradation commonly proceeds more rapidly during drought, the real causes of desertification are as follows:

- Inappropriate land management both during droughts and between droughts
- Management that does not take cognizance of normal climatic variability
- The inherent capabilities and limitations of the land

In effect, drought (however defined) is one of the risks associated with human occupation of arid lands characterized by a variable and largely unpredictable climate. Drought (especially severe drought) is often regarded as an abnormal event. But in fact it is a natural recurring feature of all arid environments. It is often said that the climate in a particular region is "characterized by frequent droughts," but this is nonsense, and furthermore, it is dangerous to think this way, because this tends to reduce human responsibility for land degradation.

From a practical viewpoint, drought is intrinsically related to climatic zones and the resistance of plants to water shortage. Thus, establishing whether there is, or is not, a drought in progress is less meaningful for arid zones, since the prospects of them remaining dry are significantly higher than of more abundant rainfall zones.

In low-rainfall regions, the amplitude of rainfall variation is relatively greater than in higher-rainfall regions (i.e., rainfall in the lowest docile is relatively much lower than in the average or higher docile) and individual periods in the lowest docile are longer. These are factors that need to be taken into account in land management systems, especially where cropping and herding are the major land uses.

For example, an analysis of drought in Australia shows that the likely pattern of drought across the Australian continent (7,600,000 km^2) in any 100-year period can be summarized as follows:

- Twenty-one years are likely to be free of major droughts.
- Sixty-two years will have droughts covering less than 20% of the continent.
- Fifteen years will have droughts covering 20%–40% of the continent.
- Two years will have droughts covering more than 40% of the continent.

These figures give some idea of the return periods, but not the severity of those periods.

Droughts are normal components of climate variability, though their effects are seriously worsened by human factors such as population growth, which forces people into drier and drier regions and inappropriate cropping and herding practices. The impacts of drought are likely to become ever more severe as a result of development processes and population increases.

Drought is a time of crisis for the land, its animals, and its people. It is a critical testing time for the sustainability of land management systems and will often determine whether the enterprise will survive and whether the productivity of the land on which it depends will be maintained. The crisis can be averted or diminished with careful planning and management. No two droughts are the same and the responses to them need to differ because the nature, extent, and degree of risks are constantly changing. This means that to best cope with drought, management must be closely attuned to climatic conditions, land resource conditions, financial and forage reserves, and prevailing economic conditions in the affected region or country.

The practical problems of dealing with drought are that the start of the disaster is very difficult to define, as well as the duration and the end time. Unlike other natural disasters, such as cyclones and wildfires, drought (at least at the outset) has no obvious physical presence. It is this insidious nature that has made drought management so complex.

Droughts often stimulate sequences of actions and reactions leading to long-term land degradation. Droughts may also trigger local food shortages, speculation, hoarding, forced liquidation of livestock at depressed prices, social conflicts, and many other disasters associated with famines that may catastrophically affect numerous groups and strata of local populations. In some instances however, droughts may contribute to the emergence of social strategies that enhance sustainable land productivity while protecting local livelihoods. The lessons learned from those countries/regions that have experienced severe drought and its attendant land degradation problems need to be more widely disseminated and put into practice in today's situation.

The majority of dryland human populations wrestle daily with persistent and almost universal poverty in their struggle to scrape a living from a harsh environment where periodic drought is a common phenomenon, soil fertility is low, and productivity is very low. In addition, traditional technologies have not kept up with the present rate of population growth and increased demands for food, fuel, and shelter. The end results are poverty, hunger, and malnutrition (Table 33.3). Unable to survive on scarce land and water resources, these poor populations are often forced to become environmental refugees, who migrate to neighboring lands and urban centers in search of relief, employment, and refuge.

Traditional coping strategies are frequently unable to deal with accelerated land degradation associated with the overuse of diminishing resources in a fragile environment. The abuse of a natural resource base by its traditional users is seldom due to carelessness or ignorance, but results from survival mechanisms under harsh conditions.

TABLE 33.3 Some Common Manifestations of Desertification

Economic Manifestations	Ecological Manifestations	Social Manifestations
Economic loss in cash	Loss of diversity in terms of wildlife, plants, and ecosystems	Migration of population from the affected area
Decreased crop yields	Loss of inland lakes	Rural poverty
Loss of farmland due to desertification	Loss of topsoil in terms of organic matter, N, P, and K	Influx of ecological refugees into urban areas
Loss of rangeland due to desertification	Decreased ground water level, increasing salinity of water	
Decreased grazing capacity in terms of the number of livestock	Increased frequency of sandstorms and associated loss of human life and livestock	
Abandoned farmland		
Abandoned rangeland		
Drifting sand effects on railway lines and highways		
Increase in suspended load raises river heights and increases flood problems		

33.4 Impacts of Dust Storms: Physical and Environmental

The environmental impacts of dust storms are wide ranging, impacting on source, transport, and deposition environments.

33.4.1 Source Environments

The impact on source environments is primarily a consequence of soil loss. During dust storm generation, nutrients, organic matter, and thus soil fertility are exported out of the source ecosystem. Consequently, there is a loss of agricultural productivity.

33.4.2 Transportation Environments

During dust transportation, many young plants are lost to the sand-blasting nature of the process at ground level, resulting in a loss of productivity. However, major dust storms have most of their impact within the atmosphere. The most noticeable effect is the reduction in visibility. This is of course dependent on the severity of the dust event. It could range from a slight haze to a major dust cloud. In the worst cases, visibility can be reduced to only a few meters. This loss of visibility can be a major hazard to aircraft and, in some cases, to motorists.

Dust particles are thought to exert a radiative influence on climate directly through reflection and absorption of solar radiation and indirectly through modifying the optical properties and longevity of clouds. Depending on their properties and in what part of the atmosphere they are found, dust particles can reflect sunlight back into space and cause cooling in two ways. Directly, they reflect sunlight back into space, thus reducing the amount of energy reaching the surface. Indirectly, they act as condensation nuclei, resulting in cloud formation [39]. Cloud formation raises the albedo of the globe, causing more solar radiation to be reflected back into space.

However, dust particles can also cause indirect heating of the atmosphere through cloud formation. Clouds act as an "atmospheric blanket," trapping long-wave radiation within the atmosphere that is emitted from the earth. Thus, dust storms have local, national, and international implications concerning global warming and land degradation. They also impact human health.

33.4.2.1 Deposition Environments

Mineral dust, it has been suggested, has an important role to play in the supply of nutrients and micronutrients to the oceans and to terrestrial ecosystems. Iron in the minerals composing this desert dust is a vital nutrient in oceanic regions that are deficient in iron. Further, more research has shown that the canopy of much of Central and South American rainforest derives most of its nutrient supply from dust transported over the Atlantic from the Sahara region of North Africa [14]. The Sahara dust occasionally reaches the State of Florida in the United States, causing a high-altitude haziness that obscures the sun. Dust from China's deserts is transported to the waters near Hawaii in the south Pacific. As the dust settles in the waters around Hawaii, the primary productivity of plankton in the water column increases [37]. This research suggests that dust transport processes form an integral part of the global ecosystem.

Yet, nutrient deposition can have negative effects. Many arid region rivers and lakes have been slowly atrophied by ongoing dust deposition. As the dust cloud moves downwind, it inevitably passes through populated areas, contributing to urban air pollution. As the dust settles over a populated area and people breathe in these tiny dust particles, those with asthma and other respiratory disorders suffer. Dust particles have been shown to cause a wide range of respiratory disorders, including chronic bronchitis and lower respiratory illness. More sinister are the health-related problems in areas where the dust is salt laden or is contaminated by toxins.

Due to the high emissions of dust in the environment, heavy metals attaching to the particles can be released on a large scale [16], and because of this, dust can be considered as an important source of heavy metals [34].

Generally, urban dust reflects the state of pollution in urban areas [27]. At the same time, when the dust phenomenon happens, the concentration of some heavy metals (including lead) rises three times [50]. Generally, heavy metals enter into the urban environment from various human sources, including industrial plants, combustion of fossil fuels, use of energy [42], and agricultural activities [38]. Heavy metals can cause serious environmental hazards. Metals such as lead, cobalt, cadmium, copper, and chromium are defined as dangerous pollutants as they can accumulate in the human body with a relatively long half-life. In addition, some ions of cadmium, chromium, and copper lead to skin diseases and various types of cancer [38]. Therefore, the study and understanding of the heavy metals behavior is significant for different reasons. One of the main studies about any pollutant is understanding the value and source of pollution. For this reason, determining the amount and source of heavy metals contained in dust as one of the factors of urban atmospheric pollution is very important. In a study on the distribution and identification of sources of heavy metals in the particulate matter (PM) in the atmosphere in India, it was found that metals such as cadmium, lead, zinc, copper, and nickel are highly enriched in comparison with the same metals in the crust of the earth. Industrial activities, exhaust from vehicles, and fuel combustion were introduced as the main sources of these metals in the atmosphere under study [2]. In another study, it became clear that the main source of contamination of agricultural soils in relation to zinc, lead, and arsenic is dust associated with mining of these metals [35].

33.5 Social and Economic Impacts of Land Degradation

For many years, the scientific community has raised the debate over the nature and the causes of desertification. The following two opposing scientific theories have been developed: (1) single-factor causation and (2) multiple-factor causation of desertification. The theory of single-factor causation uses various root causes of the phenomenon, such as demographic changes or improper land management that leads to human-induced desertification. The other theory suggests that desertification is the result of several factors that are strongly linked to the local conditions, and thus, it is impossible to draw general patterns of desertification [21].

A classification has been developed [15] of the most important feedback mechanisms that have been proposed as responsible for land degradation by several desertification theories. These mechanisms alter the properties of soils, transform the relationship between vegetation and climate, and modify the composition of plant communities. According to this classification scheme, the following three major processes of land degradation are distinguished: (1) the loss of nutrient-rich topsoil due to wind and water erosion; (2) the decrease in soil water storage capacity induced by various causes, including unsustainable agricultural practices and overgrazing; and (3) the accumulation of salts or other toxic substances in the soil. Other authors [19] particularly focused on the important distinction between factors and causes of land degradation. Based on this the factors are biophysical processes and attributes that define the type of degradation processes, such as soil erosion, salinization, soil sealing, etc., while the causes are considered as biophysical, socioeconomic, and political agents affecting the rate of land degradation. A comprehensive study carried out by the European Union (EU) research project DESIRE (www.desire-project.eu) has shown that in 17 study sites located in the Mediterranean and Eastern Europe, Latin America, Africa, and Asia, the main processes or causes of land degradation and desertification identified in these study sites were (1) soil erosion, including water and tillage erosion; (2) soil salinization; (3) water stress; (4) forest fires; and (5) overgrazing.

Moreover, the main anthropogenic factors are considered as of socioeconomic nature. One such factor is population growth and the continuous increase in water consumption, leading also to environmental pollution. Intensification of agriculture through human intervention is another factor, since overexploitation of plant biomass and irrational cultivation of hilly lands result in soil erosion. In addition, deforestation and reduction in vegetative cover due to forest fires, overgrazing of sensitive areas, land abandonment, as well as irrational land development and tourism lead to land degradation. Furthermore, the increase in surface runoff to the sea, due to deforestation and overexploitation of water resources, leads to a reduction in the available resources, resulting in salinization of groundwater aquifers and intrusion of seawater in coastal aquifers. Similarly, ineffective irrigation planning results in redundancy and losses of irrigated water, leading to soil salinity. Needless to say, problems of water scarcity, groundwater depletion, soil erosion, and salinization have all been recognized as outcomes of policy and institutional failures. In summary, the human causes of desertification are not fully understood. Changing paradigms and varying views among researchers mean that there is no consensus yet on how human factors affect desertification [40].

In general, soil degradation and desertification is affected by both biophysical and socioeconomic factors. A direct correlation has been found between the increasing soil degradation and land sensitivity to desertification in Italy and the quite complex relationships among environmental and socioeconomic parameters [41]. Changes in the socioeconomic structure of an area can be both a driving force and an impact on land degradation. Changes in the social structure of an area can occur when the local socioeconomic context has become incapable of satisfying the population's needs. This may be the result of land degradation caused by humans in the landscape over time, or due to low land productivity, affecting the income of the population. When such problems arise, degraded areas are abandoned, deprived of the conditions that might mitigate the problem, for example, by encouraging the use of good management practices to avoid destructive phenomena. Studies carried out by the EU research project DESIRE in areas prone to desertification have shown that population density, population growth rate, old age index, allocated subsidies, land fragmentation, and land ownership can greatly affect the vulnerability to desertification. Areas affected by soil erosion or water stress are more vulnerable to land degradation and desertification under high population densities (higher than 100 people/km^2). Areas with a high population density are usually subjected to high rates of burned area. Furthermore, areas with a low population density are mainly characterized with high rates of land abandonment, affecting desertification positively or negatively depending on the characteristics of the physical environment.

Population growth rate is especially important for forested areas affected by fires. Low population growth rates along with a high old age index lead to decreasing animal population grazing the forested land and increasing forest fires due to higher remaining flammable biomass. In the opposite, areas characterized by high population growth rates are mainly characterized as supporting low vegetation cover, which increases water runoff and land degradation. The old age index is related to the application of land management practices and to the introduction of new technologies. Older people tend to follow traditional land management practices, while younger farmers are relatively easily convinced to introduce new technologies and land management practices that consider the sustainability of land resources.

The human aspects are related to both population pressure and land-use technologies that are not sustainable, as they have not developed alongside the rapid population growth that is being witnessed in the Third World but whose negative effects hit drylands most. The best known of these land-use technologies is the fallow system, which in earlier times involved the resting of exhausted land long enough to allow fertility recovery through secondary vegetation. This original time span has been shortened and is almost nonexistent now as a result of land pressure, especially in the African drylands. Clearing of vegetation, rapid abandonment of exhausted cropland, and expansion of cropping into more and marginal land have set up a vicious cycle that is hard to break. Figure 33.9 is a flowchart showing the typical sequence contributing to this cycle of poverty [40].

As much as the inherent ecological fragility of drylands, coupled with recurrent droughts, increase the degree of susceptibility to human-related land degradation processes, so do the latter affect the impact of drought through the weakening of the resilience of the system and the ability to return to equilibrium. Devastating dust storms are a common symptom of the rapidly deteriorating ecological situation.

Land degradation through loss of vegetation and soil cover contributes to global climate change by increasing land surface albedo, increasing the potential but decreasing the actual evapotranspiration rate, changing the ground surface energy budget and adjoining air temperature, and adding dust and carbon dioxide to the atmosphere.

Impacts of land degradation on the natural resource base, with a direct effect on human populations, include:

- Reduction in perennial and annual livestock forage in rangelands
- Reduction in available fuel wood material
- Reduction in biodiversity
- Reduction in water availability due to a drop in the water table
- Sand encroachment on productive lands, human settlements, and infrastructure
- Increased flooding as a result of sedimentation of water bodies
- Reduction in yield or crop failure in irrigated or rainfed farmlands

All these factors may ultimately lead to disruption, in various degrees, of human life due to deteriorating life support systems, which is expressed by:

- An increase in the spread of poverty and hunger due to loss of land resources and consequent inability to provide sufficient food and shelter to growing populations, leading to a reduction in the nutritional and health status of the affected populations, especially the young and the elderly
- Migration in search of relief and refuge as a result of economic and political stress, as populations struggle to survive on the diminished water and land resources
- An influx of environmental refugees, which puts enormous pressure on the physical environment, economy, and stability of societies in the immediate neighborhood, often exacerbating political differences and, in some cases, civil strife

The solution to desertification, if there is one, is to shift the emphasis from land to people. Desertification control should be about people who use the land, not about the land they use.

As the few case studies show, there are many regions where dust storms and drifting sand are real problems faced on a day-to-day basis by local populations and by government land management specialists and advisors. Experiences in the Dust Bowl of North America should be both a warning and a source of comfort. Faulty land-use practices, poor farming/herding methods, and inappropriate government policies can lead to an acceleration of land degradation in drylands (Figures 33.5 and 33.6). The good news is

FIGURE 33.5 Black blizzards, like the one experienced in North America during the Dust Bowl era, can develop when poor land management, shortsighted policies, and drought combine.

FIGURE 33.6 Dust storms have a serious impact on people's wealth, health, and spirit. They can destroy whole communities and impose high economic costs on a region or nation.

that something can be done if the problem is properly analyzed and if there is a serious attempt to mobilize all the stakeholders in finding a solution. The solution may well be to relocate people and abandon attempts to crop or graze the badly degraded areas. The National Action Plans of each signatory to the UNCCD should reflect all options and develop a program with verifiable targets and an agreed time frame that is known to the public (Figures 33.7 through 33.9).

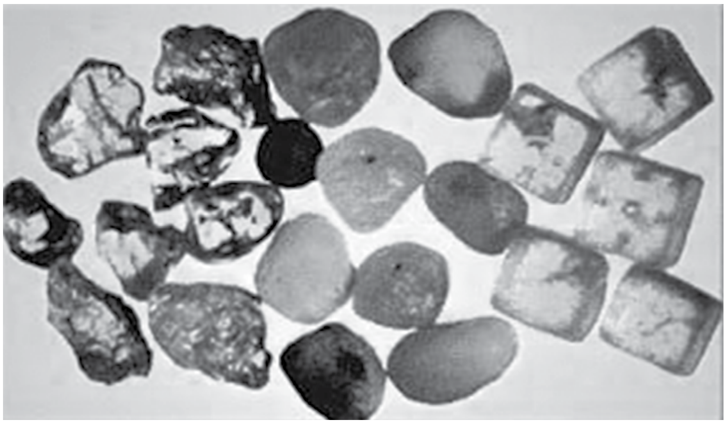

FIGURE 33.7 Sand grains are not all the same. The size and density will determine the behavior of sand particles when subjected. Quartz sand grains compared with cubical crystals of ordinary table salt (NaCl). Left: Angular sand grains from the Algodones Dunes. Middle: Rounded highly polished sand grains from Sand Mountain, a booming dune. Right: Cubical crystals of ordinary table salt.

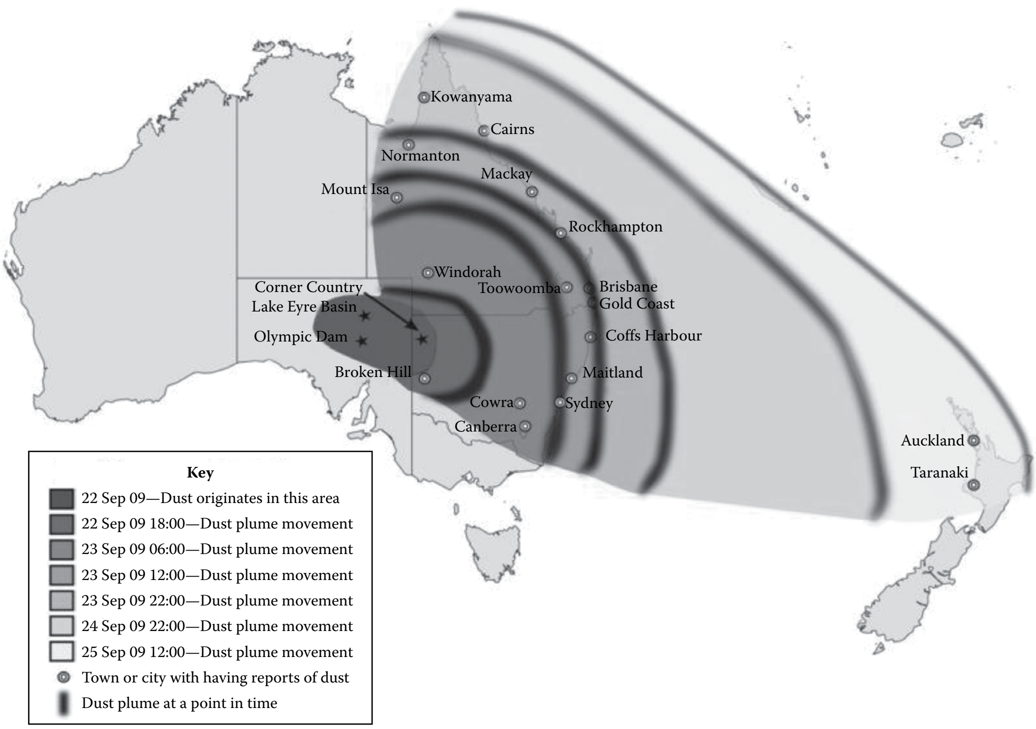

FIGURE 33.8 Frequency and distribution of dust storms in Australia.

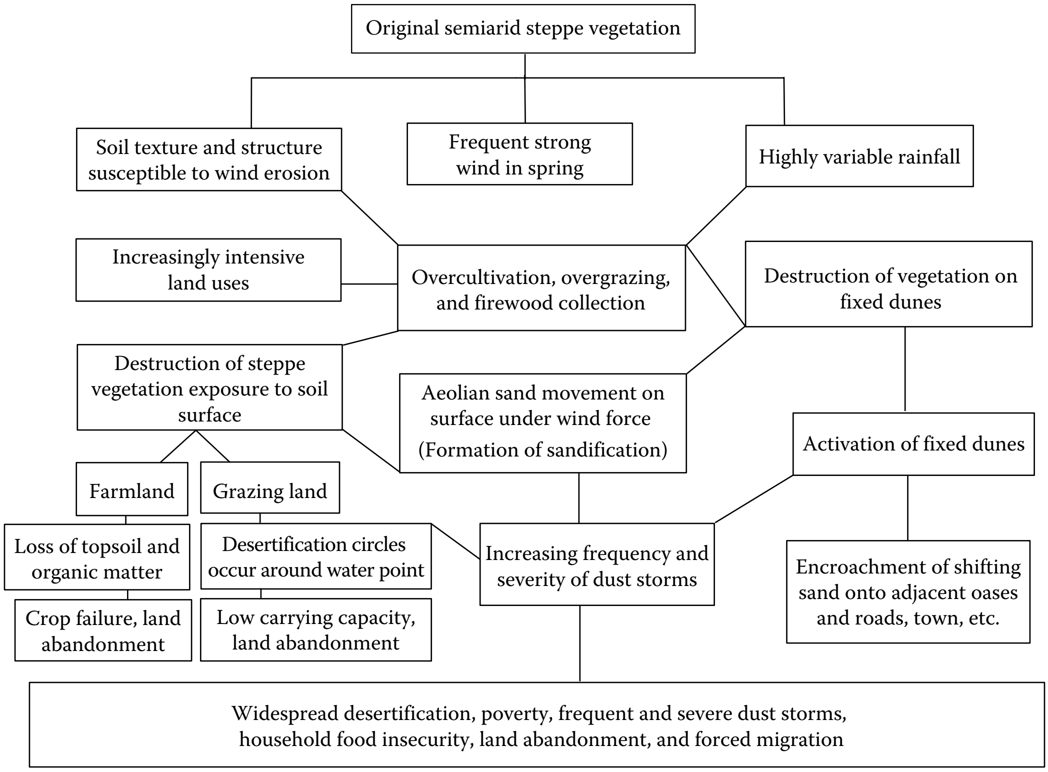

FIGURE 33.9 Desertification flowchart.

33.6 Natural Factors Involved in the Formation of Severe Sandstorms

- *The connection with the atmosphere*: The areas where strong sandstorms occur frequently and seriously are mainly located in dry and semidry areas of middle latitudes, and they are also the very areas that are greatly influenced by and suffer under desertification. What is more, these areas are very sensitive toward the changing global climate and can cause negative effects [40].
- *Very cold air is the driving force of sandstorms*: Only when the air is cold enough is it possible for strong air pressure gradients to form. Abundant dry and loose sand material is the surface condition to form sandstorms. When the airflow is driven by strong wind power and there is no vegetation cover on the earth surface, the airflow can carry a lot of surface dust, silt, and sand to float in the air and form sandstorms. The height of a sandstorm can be 1000–2500 m when it is not serious and 2500–3200 m when it is serious.
- *The formation of sandstorms needs a stable heat layer on the earth surface*: There is always a continuous high-temperature weather several days before the occurrence of sandstorms, which promotes the rising of the airflow and increases the disturbance of the airflow to the surface, so in spring, with changes in temperature, it is easiest to form sandstorms.
- *The formation of strong sandstorms and geographical factors*: The landform relief has important actions as direction guide and "landform effects" to form sandstorm weather. Landforms that characterize the topography of the Northwestern Area are mountains that alternate with basins as well as plateaus and plains. For example, the Zhunger Basin lies in the middle of the Tianshan Mountain and the Aertan Shan Mountain; the Talimu Basin lies in the middle of the Tianshan Mountain and the Kunlun Mountain.

The Hexi Corridor lies to the north of the Qilian Mountain and the Aerjin Mountain and to the south of the Alashan Plateau–Baishan upheaval belt alongside the terrace. The high plain of the Corridor is in the middle. For the run of sandstorms, a role of direction guide and consolidation is played by the landform. It also plays a role in increasing the air pressure and temperature gradients, which bring about the occurrence of the sandstorm weather. The sandstorm weather often occurs in inland desert areas. As such, areas of frequent sandstorms include the Taklamakan Great Desert, the Badanjilin Desert, and the Tenggeli Desert, in northwestern China, so it is known as a frequent area of sandstorms [47].

- *The relationship between the formation of strong sandstorms and vegetation*: In dry and bare arid areas, large expanses of sandy land and sand provide abundant sand and dust sources for the formation of sandstorms. Where the land surface has a cover of shrubs, the vegetation changes the coarseness of the surface; this increases the resistance of the surface to the airflow and changes the airflow structure of the surface layer near the surface. According to surveys and research, when the airflow enters grassland belts from bare areas, the roughness of the land surface can increase from 8×10^4 to 3×10^5 times and the resistance to the airflow could increase 17–26 times, while the drag coefficient can increase 4–5 times. In an area with shrubs and grasslands whose width is at least 244 m, the energy supply of the airflow at the upper layer to the airflow near the surface can decrease, which decreases the wind speed near the earth surface by 40%. At a height of 10 cm, the wind speed can decrease by 90%.

33.7 Human Factors Involved in the Formation of Severe Sandstorm Weather

Human activity plays an important role in the formation of sandstorms and mainly includes two aspects: the first one is irrational land use. The office of environmental planning of UNEP analyzed the human factors of global desertification and pointed out that overgrazing caused 34.5% of the degraded land area, forest damage caused 29.5%, and irrational local agricultural use caused 28.1%. Other factors such as irrational use of water resources, mining, and transportation caused 7.95% of the degraded land area. The situations are similar in China. The second aspect is population growth and the rapid development of urbanization, which increase the pressures on the current productive land. Peasants pursue short-term action to improve their life through intensified economic activities. The human factors are discussed in detail as follows [40].

33.7.1 Excessive Cultivation

Land fragmentation can affect land management practices and decision-making related to the structure of the farm. A highly fragmented land is not easily mechanized and is usually cultivated in a direction in which soil erosion is not restricted. Farm ownership represents a fundamental consideration for decision-makers in formulating political measures to help individual farmers or to the affected community as a whole. Farm ownership is related to land-use intensity. Land-use intensity is mainly characterized as low to moderate in areas characterized as owner farmed, while high land-use intensity can be mainly identified in areas characterized as tenant or state farmed. Farm subsidies have ensured an adequate income to farmers for maintaining landscapes, especially in less-favored areas, but this support has favored the intensification and specialization process in agriculture by applying more fertilizers and pesticides, irrigating the land, increasing the number of animals, etc. Under this financial support, unproductive agricultural areas cultivated with cereals, critical to desertification, have remained under cultivation, leading to further deterioration of soil conditions. The number of animals has increased to unsustainable levels, causing severe degradation in vegetation and soils in grazing lands.

In the north part of China, half of the cultivated land was opened up during the 10 years of cultivation. The national office of agricultural regionalization carried out the survey of Landsat remote sensing for 10 years in 53 county units in Heilongjiang, Inner Mongolia, and Xinjiang from 1986 to 1996. They discovered that in these four Northern provinces, the situation of damage to grassland and forests has become very serious over the last 10 years. Nearly half of the cultivated land was opened up. During the last 10 years, the cultivated area has come to a total of 1.74 million ha, but the preserved cultivated land area is only 884,000 ha, which comprises 50.8% of the total cultivated area. The local people have expressed this situation sadly: "to cultivate grassland in the first year, to get a little grain in the second year and to turn them into sand in the third or fifth year." The abandonment of cultivated land formed a large area of sandy land, enlarged desertification, and provided abundant sandy material for the formation of sandstorms. From history, it can be seen that some large areas of sandy land are related to farming cultivation and wars on a large scale. The three great episodes of cultivation since the foundation of New China destroyed a large area of natural vegetation. In many places where conditions of cultivation are not enough and there are no protection measures, cultivation without plans and limitations brought about land desertification.

33.7.2 Excessive Deforestation

Natural desert forests distributed around deserts and sands are outcomes of a natural balance formed over a long time. Combined with all kinds of artificial forests with large planting areas (including shrubs), they form the protection system, which is an important part of a stable ecological system in desertified areas. In western regions of China, for reasons of excessive deforestation, there is no single vital force in the fragile ecosystem and sands occur everywhere. For example, in the areas along the lower reaches of the Talimu River, the area of populous diver's folia (euphratica) forest has decreased from 53,000 ha in the 1960s to 13,333 ha. It decreased 75%. In the transition area of grassland and forest in the Bashang area, due to excessive deforestation, the ecological environment was seriously destroyed. According to an interpretation analysis of Landsat images, from 1987 to 1996, the forest area decreased from 363,500 to 222,400 ha, by 38.82%. The area of flow sands increased from 68,000 to 129,100 ha, by 81%.

33.7.3 Excessive Grazing

Excessive grazing can lead to the degradation of grasslands. At present, in northwestern areas of China, nearly 70% of grasslands are degraded because of excessive grazing. The overloading rate of animals in grasslands is 50%–120%. It can be as high as 300% in some places. In the Hunshandake Sands, excessive grazing brought about desertification. In 7 years, from 1989 to 1996, the area of flow sands increased by 93.3%. The area of grassland decreased from 602,500 ha in 1989 to 430,100 ha in 1996, by 28.6%. Moreover, for the irrational distribution of grazing spots and watering points, the vegetation of grasslands was destroyed seriously and wind erosion increased.

33.7.4 Abuse of Water Resources

In the northwestern arid and semiarid areas of China , the sources of total water resource are precipitation, surface runoff, and underground water. The use of water resources falls short of scientific management. The situation of waste is very serious. In the upper reaches, for lack of a strict system of irrigation, the amount of irrigation is too large. The serious shortage of water resources and uneven distribution brought about difficulties for ecological water in the northwestern areas, which caused a large area of natural desert forest to die and vegetation to wither. Continuous activities for economic buildup including the development of water resources have led to the lower reaches of the particular river drying up, the excessive exploitation of groundwater, soil and water imbalance, and an increase in desertification.

33.8 Overview of Air Pollution Problems in Iran

Air pollution in Iran has significant natural and anthropogenic sources. The primary anthropogenic sources are industrial activities and transportation, both of which are centered in urban areas, while the main natural source is wind-blown dust [47]. The capital city of Tehran, with a population of more than 8 million, is the largest metropolitan area in Iran. Tehran's population has increased from about 700,000 in 1941 to more than 7 million in 2005, and today it has a population density of approximately 10,000 inhabitants/km^2. The annual mean precipitation and temperature are about 230 mm and 17°C, respectively, with a mild continental climate, featuring hot summers (mid to high thirties) and moderately cold winters (just below zero).

Air pollution in this overpopulated city has grown significantly over the past decade. With 3 million vehicles, nearly half of the country's industrial firms, and more than 10% of the country's population, the city has exceeded its natural carrying capacity and is no longer sustainable, resilient, or healthful [5]. Inhabitants of Tehran are generally exposed to high levels of background PM due to the large number of anthropogenic sources, aggravated by the city's topography, which includes a high-altitude mountain chain, downstream of the prevailing wind. Even during regular days (not "dusty" days), PM10 concentration in Tehran is more than double the World Health Organization's (WHO) 24 h mean recommendation of 50 μg/m^3. On dusty days, this already-elevated PM10 concentration rises significantly to levels more than three times greater than what WHO guidelines recommend.

33.9 Dust Sources

Dust is the generic term for fine airborne particulates usually smaller than 1 mm. Very fine particulates, smaller than 10 μm (PM10) and smaller than 2.5 μm (PM2.5), can get trapped in the lung membrane, causing health problems [9]. Iran, like many other Middle Eastern countries, is affected by multiple dust storms each year, especially in the eastern, western, and central regions, which includes Tehran. Such episodes generate high levels of PM, which impairs visibility and causes elevated morbidity [23].

Dust activity is visible over much of the country for about half of the year, with the activity being the lowest in winter and peaking in May, June, and July. Observations from the National Aeronautics and Space Administration's (NASA) Total Ozone Mapping Spectrometer (TOMS) have been used to validate the timing of dust events according to ground meteorological stations in Iran, as well as to characterize primary dust source areas. Data show that the primary sources of dust in Iran are the deserts of the Middle East and Arabian Peninsula, as well as intermittent and dry lakes and marshes, including the Dasht-e-Kavir desert, which includes the Daryacheh-ye Namak salt lake; the Hamun-e-Jaz Murian salt lake; the Hamun/Hamoon lakes and swamps on the Iran–Afghanistan border; and the Al-Hawizh/Al-Azim marshes along the Iran–Iraq border.

33.9.1 The Hamoon Lakes

The Hamoons are classified as freshwater wetlands and form the political boundary between Iran and Afghanistan. When these Hamoons do not get enough water, either due to drought or diversion, or during the natural dry periods of the year (April–September), they convert into drylands, where playa and tiny sediments are exposed to the atmosphere. Simultaneously, strong (up to 110–120 km/h), low-altitude winds occur seasonally in this area in a southwesterly direction, picking up exposed sediments as they blow across the basin [18] (Figures 33.10 and 33.11).

33.9.2 Contribution of the Middle Eastern Dust Source Areas to PM10 Levels in Tehran

The majority of the dust affecting Tehran, and Iran in general, arises in the vast deserts of the Middle East, to the southwest of Iran, where prevailing winds carry the dust east across the Persian Gulf and into Iran. A source apportionment study shows that dust comes mainly from the subregions, including the areas in northern Iraq and eastern Syria [23] (Figure 33.12).

33.9.3 Lake Urmia Drying Out: A New Environmental Disaster

Lake Urmia, located in the center of the closed Urmia Basin and west of the Caspian Sea, is one of the most important and valuable ecosystems in the country. It is the largest inland lake in Iran, and because of its

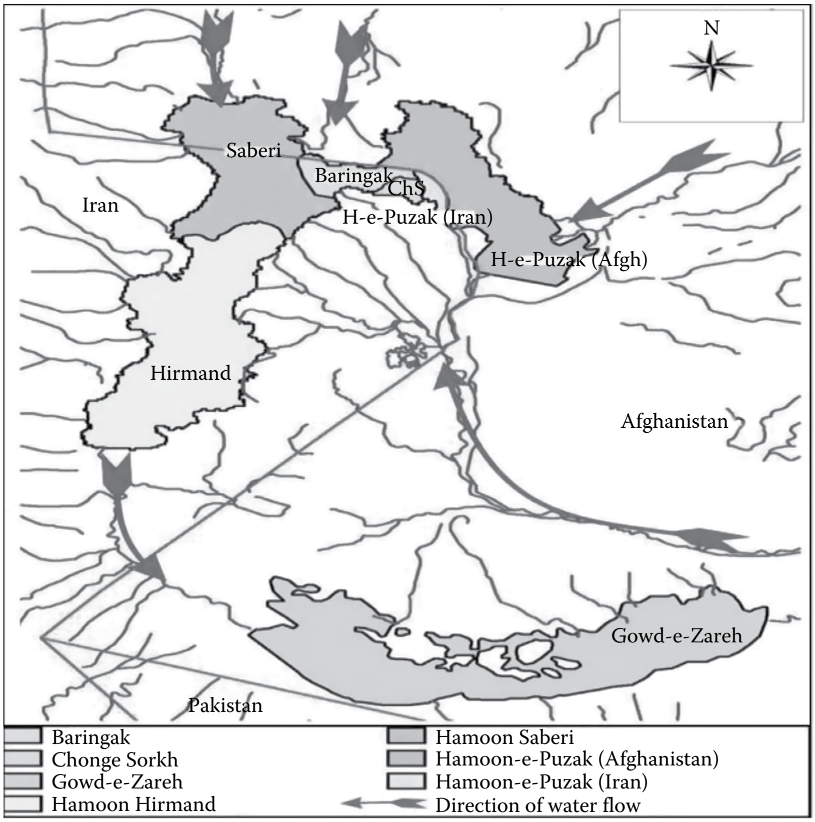

FIGURE 33.10 Subdivision of the Hamoons with the main directions of water flow. (From United Nations Environment Programme [UNEP], History of environmental change in the Sistan Basin based on satellite image analysis: 1976–2005, UNEP report, Geneva, Switzerland, 2006.)

unique natural and ecological features (being a permanent hypersaline lake), it has been given a national park status and has been designated as a Ramsar site (wetland of international importance) since 1975 and a UNESCO Biosphere Reserve since 1977 (Figure 33.13).

In 1990, the lake's surface area was estimated to be 5263 km^2. However, since 1995, the lake has been gradually shrinking due to unsustainable withdrawals for agriculture. It is estimated that 70% of the lake has dried up over the past 30 years; as with the Hamoon lakes and marshes, this shrinking process exposes fine sediments, which are then prone to being released into the atmosphere.

In fact, studies show that dust (mainly salt, with some small PM) from Lake Urmia can attain an altitude of up to 1000 m in height before being distributed primarily northward toward a region with a radius of more than 250 km. While not a national problem, this is a significant regional problem in the surrounding cities and agricultural areas [25].

33.9.4 Assessment of Chemical and Mineralogical Characteristics of Airborne Dust

Wind-blown transport and deposition of dust is widely recognized as an important physical and chemical concern to climate, human health, and ecosystems. Sistan is a region located in southeast Iran with extensive wind erosion, severe desertification, and intense dust storms, which cause adverse effects on regional air quality and human health. To mitigate the impact of these phenomena,

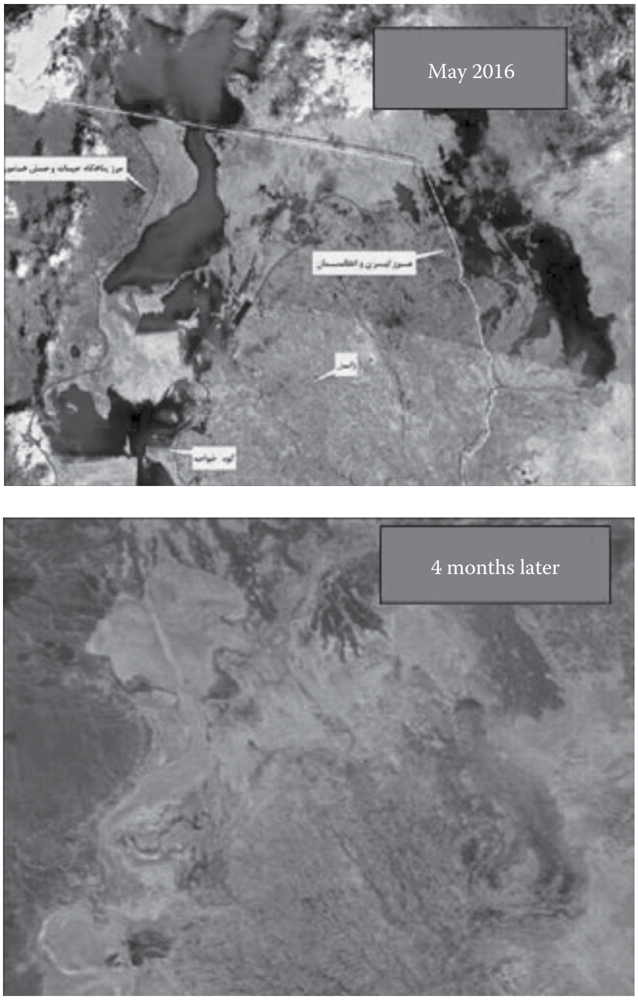

FIGURE 33.11 Hamoon lakes drying out.

it is vital to ascertain the physical and chemical characteristics of airborne and soil dust. For the first time, the mineralogical and chemical properties of dust over Sistan were studied by collecting aerosol samples at two stations established close to a dry-bed lake dust source region, from August 2009 to August 2010. Furthermore, soil samples were collected from the topsoil (0–5 cm depth) at several locations in the dry-bed Hamoun lakes and downwind areas. These data were analyzed to investigate the chemical and mineralogical characteristics of dust, the relevance of inferred sources, and contributions to air pollution. X-ray diffraction (XRD) analysis of airborne and soil dust samples shows that the dust mineralogy is dominated mainly by quartz (30%–40%), calcite (18%–23%), muscovite (10%–17%), plagioclase (9%–12%), chlorite (~6%), and enstatite (~3%), with minor components of dolomite, microcline, halite, and gypsum. X-ray fluorescence (XRF) analyses of all the samples indicate that the most important oxide compositions of the airborne and soil dust are SiO_2, CaO, Al_2O_3, Na_2O, MgO, and Fe_2O_3, exhibiting similar percentages for both stations and soil samples. Estimates of enrichment factors (EFs) for all studied elements show that all of them have very low EF values, suggesting natural origin from local materials. The results suggest that a common dust source region can be inferred, the extensive Hamoun dry lakes to the north of Sistan in which eroded sediment is dominant.

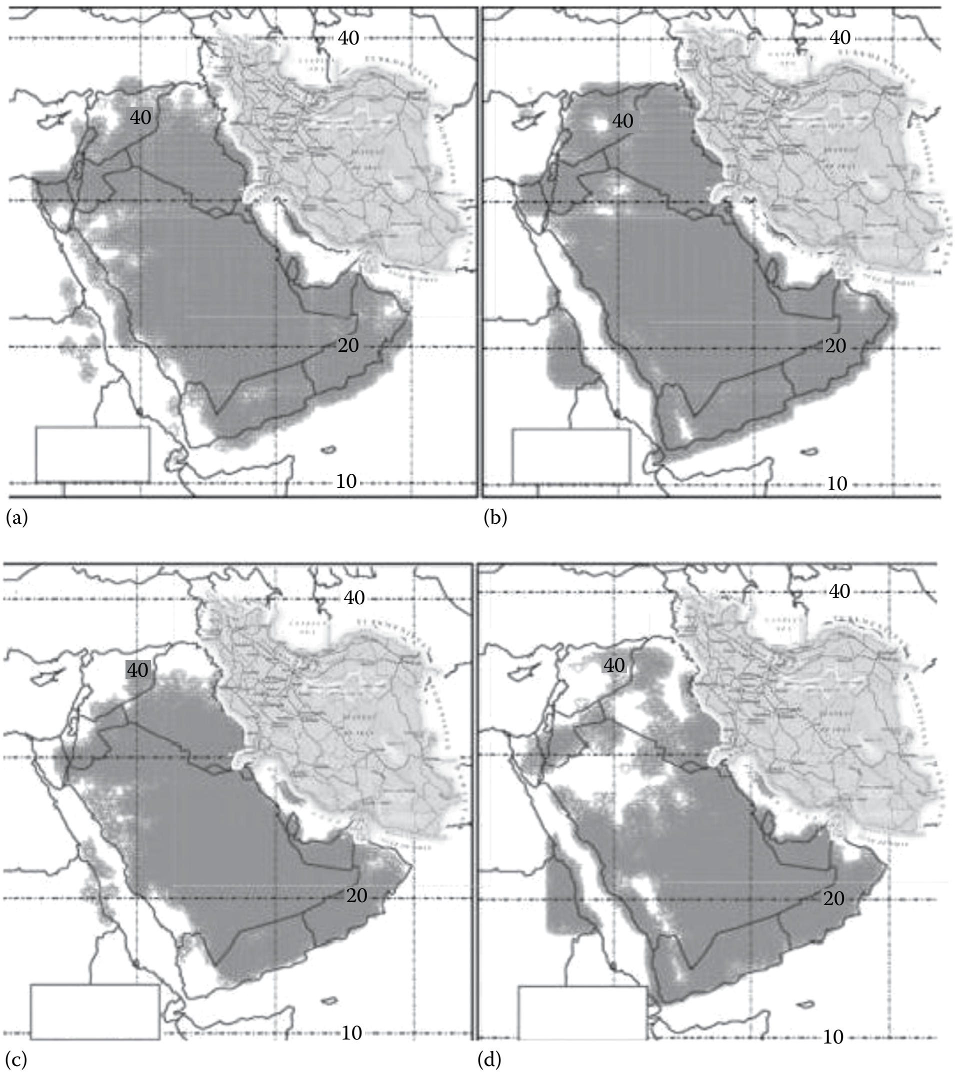

FIGURE 33.12 Potential dust origins during different months of the year, including (a) January, (b) April, (c) July, and (d) October.

The mineralogy and physicochemical properties of atmospheric particulates were investigated by collecting samples at Abadan (southwestern Iran) near the Persian Gulf coast and Urmia (northwestern Iran) during ambient and dust events for over 6 months (winter 2011; spring 2012). Particle sizes collected were TSP (total suspended particulates), PM10 (particulates <10 mm), and PM2.5 (particulates <2.5 mm). Minerals were identified using XRD; particle morphology and composition were examined by scanning electron microscopy and energy dispersive X-ray spectroscopy (SEM-EDX). Major minerals detected were calcite, quartz, clay minerals, and gypsum, with the relative abundance related to sampling site, collection period, wind direction, sampling head, and total sample amount. The anomalously high calcite content appears as a characteristic feature originated from calcareous soils of the region. SEM observations indicated a wide range of particle morphologies over the 1–50 μm size range, with spherical, platy, cubic, elongate, and prismatic shapes, and rounding from angular to round. Energy-dispersive X-ray analysis of TSP samples from both sites for nondusty periods

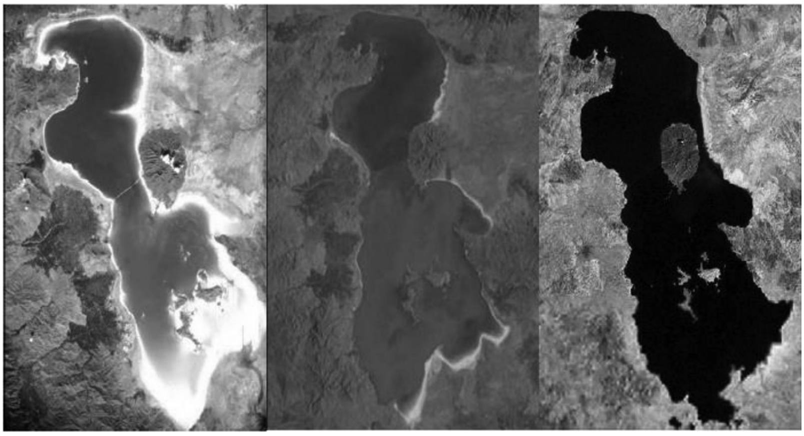

FIGURE 33.13 Lake Urmia drying out.

indicated that the sampled mineral suite contained Al, Mg, Na, Cl, P, S, Ca, K, Fe, Ti, and Si, mostly reflecting calcite, quartz, aluminosilicates, clays, gypsum, and halite. Additionally, As, Pb, Zn, Mn, Sc, Nd, W, Ce, La, Ba, and Ni were detected in TSP, PM10, and PM2.5 samples [1] collected during dust events.

33.9.5 Natural Sources of Nanoparticles

Nanoparticles are abundant in nature, as they are produced in many natural processes, including photochemical reactions, volcanic eruptions, forest fires, and simple erosion, and by plants and animals, for example, in shed skin and hair. We usually associate air pollution with human activities—cars, industry, and charcoal burning, natural events such as dust storms, volcanic eruptions, and forest fires can produce such vast quantities of nanoparticulate matter that they profoundly affect air quality worldwide. The aerosols generated by human activities are estimated to be only about 10% of the total, the remaining 90% having a natural origin [48]. These natural large-scale phenomena are visible from satellites and produce PM and airborne particles of dust and soot ranging from the microscale to the nanoscale. Small particles suspended in the atmosphere, often known as aerosols, affect the entire planet's energy balance because they both absorb radiation from the sun and scatter it back into space [26]. It has been estimated that the most significant components of total global atmospheric aerosols are, in decreasing mass abundance, mineral aerosols primarily from soil deflation (wind erosion), with a minor component (<1%) from volcanoes (16.8 Tg); sea salt (3.6 Tg); natural and anthropogenic sulfates (3.3 Tg); products of biomass burning, excluding soot (1.8 Tg), and products of industrial sources, including soot (1.4 Tg); natural and anthropogenic no methane hydrocarbons (1.3 Tg); natural and anthropogenic nitrates (0.6 Tg); and biological debris (0.5 Tg) [6] ("Tg" here denotes terragram, equal to 1012 g).

33.9.6 Biological Stabilization of Fine-Grained Soils

The application and the influence of traditional dust suppression methods, including spraying water, salts, chemicals, and petroleum products on airborne dust particles, are well studied [17]. Environmental pollution, hazards, high expense, and fire potential are some of the many disadvantages of these methods. One of the methods that is environmentally safe and satisfies environmental criteria is bio-stabilization or bio-cementation. In the bio-stabilization or bio-cementation process, fine and very fine particles of soil are coagulated by a mineral or an organic agent, which is produced by mosses, liverworts, algae, lichens, fungi, bacteria, or cyanobacteria or any other micro- or macro-organisms.

During the last two decades, researchers have shown a growing interest in investigating microbiotic soil crusts in arid and semiarid habitats [28]. These crusts consist of lichens, bryophytes, algae, microfungi, cyanobacteria, and bacteria growing on or just below the soil surface within the interplant matrix. Soil crusts of this type are known by a number of names, including cryptogamic, microphytic, microfloral, cryptobiotic, and microbiotic. One of the important roles of microbiotic soil crusts is soil stabilization, resulting in a reduction in erosion by wind and water. Early studies investigated the binding of soil particles and the cementation of soil surface by algal filaments and fungal mycelium [36].

It is noteworthy that the cementation (binding) material can be a mineral or an organic compound. Calcium carbonate ($CaCO_3$) is a common mineral agent that is induced by a certain type of microorganism [3]. In the process of bio-mineralization, a urease enzyme is produced by these microorganisms, which results in the hydrolysis of urea and consequently the production of both ammonium and carbonate ions. This reaction raises the pH of the surrounding environment, ultimately precipitating calcite from carbonate and calcium ions.

The cementation process can also be achieved by an organic agent, which binds together small particles into larger particles. Several mechanisms can contribute to this binding process, among which the following mechanisms are noteworthy: physical binding of soil particles by entangled filaments, adhesion to sticky sheets or slime layers (e.g., polysaccharide network excreted by microorganisms such as microalgae), and attachment of particles to sites along the microorganism's cell wall. This binding improves the soil's resistance to both wind and water erosion. After a dry weather cycle, the microorganisms die, but the polysaccharide network still adheres to the sand grains. This cementation process, thus, can be naturally made and is very often found in the so-called microbiotic soil crust. As mentioned before, microbiotic crusts are formed by living organisms and their by-products, which create a surface crust of the soil. The microbiotic crust consists of soil particles bounded together by these organic materials. Having been inspired by these natural cementation mechanisms, scientists have, recently, examined the use of adhesive by-products of metabolic paths of microorganisms for improving soil mechanical and hydraulic properties.

33.10 Climate Change Activities in Iran under UNFCCC

Iran is highly vulnerable to the adverse impacts of climate change. It is an arid to semiarid country with limited water and forest cover that is susceptible to extreme weather events and desertification and has high urban air pollution, fragile mountain ecosystems, and an economy highly dependent on production, processing, and export of fossil fuels. A vulnerability and adaptation (V&A) assessment study was conducted to assess the adverse impacts of climate change on the country's water resources, agriculture, forestry, coastal zones, human health, and biodiversity.

33.10.1 Impact of Climate Change on Water Resources

Modeling results indicate temperature and precipitation changes in the range of ±6°C and ±60%, respectively. Such a temperature rise not only increases evaporation and decreases runoff, but also accelerates snow melt; this in turn decreases runoff and water availability in spring. Modeling results also show that at a constant level of rainfall, an increase in temperature of only about two degrees increases evaporation and transpiration over Iran annually. Furthermore, the results prognosticate that runoff will decline in all but three regions in Iran. This will have important consequences on surface and underground water resources and thus the availability of water for irrigation and other uses in these areas.

As an adaptation measure and in order to preserve the already depleted groundwater resources, plans are in place to increase the utilization of surface water resources from the present level of 46%–55% within the next 20 years. Hydroelectric potential in Iran is over 25,000 MW; of this, 6,700 MW is currently utilized, with about 6,000 MW under construction. Due to the reduction in river runoffs under climate change projections, the efficiency of hydropower plants will decrease—adversely impacting plans for further dam construction. As an additional adaptation measure and in order to store large quantities of freshwater, construction of underground catchment systems and reservoirs is being considered.

33.10.2 Impact of Climate Change on Agriculture

The agriculture sector accounts for about 18% of national GDP, more than 20% of employment, 85% of the food supply, 25% of nonoil products, and 90% of the raw materials used in agro-industry. Agricultural activities in Iran are quite diversified and include the production of various staple crops, fruits, and nuts; greenhouse cultivation; agro-forestry; poultry; small and large livestock industries; apiculture; silkworm farming; and fisheries. In 2004, close to 90% of the total national agricultural production came from irrigated lands. Due to this dependency on irrigation, arid regions of the country are particularly vulnerable to climate change and to water availability reductions [7].

Cereals, particularly wheat, are the most important annual crops produced in the county. For the years 2020, 2050, and 2080 (based on a 1990 baseline), under various scenarios of economic growth, cereal production will decrease by 30% without the CO_2 effect and up to 10% with the CO_2 effect. For rainfed wheat production, yield reduction of up to 26% by 2025 and 36% by 2050 is predicted. For irrigated crops, the results of future weather simulation for 500 ppm CO_2 concentration in certain provinces have shown a 0.3%–9.8% increase in yield and a 4%–16% decrease in the water requirement of sugar beet.

33.10.3 Impact of Climate Change on Forests

Forests in Iran have undergone serious fragmentation and degradation because of roads, agriculture, and development and are thus impeded in their ability to migrate as their local climate changes. Temperature and precipitation patterns in the Hyrcanian forest in the north of Iran have changed during the last half-century. A warmer climate and changes in precipitation precedents will cause disparate effects on forest ecosystems, making some species contract and others expand. Increases in CO_2 concentration will compound this effect in some systems while dampening the impact in other systems, which may lead to the extinction of some species.

33.10.4 Impact of Climate Change on Coastal Zones

33.10.4.1 Caspian Sea

The Caspian Sea, being a closed basin, demonstrates much higher rates of sea-level change (up to 340 mm/year) than the oceans, experiencing a sea-level rise of 3 m between 1929 and 1995. The sea-level fluctuation impacts the basin architecture and changes the coastal morphology, which leads to the formation of new aquatic environments and forces migration of those organisms capable of moving. As the Caspian coast is both the focal point for economic activities in the north of Iran and the most biologically productive area of the sea, any changes in the sea level have a great influence on the region. Based on some scenarios, a sea-level rise will inundate more than 300 km^2 of the coast, affecting more than 2,000,000 people and causing damage estimated at 5 billion USD.

33.10.4.2 Persian Gulf

The average sea surface temperature of the Persian Gulf in some parts has risen up to 2.5°C during the last two decades. It is predicted that the trend of rising sea surface temperature will continue as precipitation decreases on an average of about 0.6 mm/year in the next 100 years. This region is also characterized by dust storms, which increase the suspended load of the water and its turbidity. The rise in temperature is already apparent, as seen in the bleaching of coral reefs in the Persian Gulf during recent decades.

Decreasing precipitation and the consequent reduction in river discharges, accompanied by direct human activities, create conditions for seawater intrusion into coastal aquifers in the northwest flank of the Persian Gulf.

33.10.4.3 Oman Sea

Tropical storms in the Indian Ocean are the primary factor for creating long waves in the Oman Sea. Their maximum speed and motion track, durability, and frequency are variable. The study of these storms reveals that their frequency and strength, as well as the probability of their reaching the Iranian coasts, have increased during the last 30 years. The increasing strength and frequency of the storms, in combination with the sparse vegetation of the area, will enhance soil erosion and carry large amounts of alluvium to the Oman Sea during flash floods. Strong waves will also contribute to coastal erosion along the predominantly rocky coastline.

33.10.4.4 Human Health

In Iran, the major climate change–related health issues include malaria, leishmaniasis, cholera, diarrhea, air and water pollution, and some natural disasters. Two periods (1995–2005 and 2010–2039) were studied for climate change impacts (mostly due to temperature and precipitation) on human health. An epidemiologic study of leishmaniasis showed increasing outbreaks of the disease (an incidence rate of up to 175% greater) in Isfahan province and Kashan, largely due to ecological changes that alter the disease vector's habitat. A study on cholera also revealed an outbreak of this disease in some provinces.

33.10.4.5 Biodiversity

Iranian habitats support some 8200 plants species, of which 2500 are endemic; over 500 species of birds; 160 species of mammals; and 164 species of reptiles (26 endemic species). Iran has 22 Ramsar Convention–recognized wetlands, which collectively encompass 1,481,147 ha and are considered extremely important ecosystems for local biodiversity and migratory birds. These wetlands are among the ecosystems in Iran most vulnerable to climate change. At present, Iran is losing its biodiversity at an alarming rate—a phenomenon that is likely linked to climate change.

33.11 Strategies against Desertification

Over the last five decades, impacted by prolonged drought and irrational human economic development activities, the eco-environment of Alxa prefecture, western end of Inner Mongolia, has sharply degraded from the former gradual deterioration [53].

Other countries in the world have had experiences of serious land degradation during the last decades:

- On May 15, 1933, a serious black dust sandstorm was observed on the Great Plain of the United States. This dust storm swept two-thirds of the North American continent, with a coverage 2400 km long and 1440 km wide. The dust transported reached a height of 3 km and soil particles landed several hundred kilometers away in the Atlantic Ocean. This was the world-famous "Dust Bowl," which took place in the 1930s in the United States.
- From 1954 to 1964, the government of the former Soviet Union opened 250,000 km^2 of steppes and rangeland in the northern Kazakhstan Republic for agricultural use. This new cultivation covered 42.1% of the total steppes of Kazakhstan. The former scene of "fresh breeze moves grasses on green rangeland" was completely polluted. The annual frequency of the dust sandstorm was 20–30 days. It was tested that 550 tons of yellow sand was deposited in a profile 100 m long and 1 m above ground under a wind force that was 6–7 on the Beaufort scale in a span of 12 h. Wind erosion and deflation have brought about serious land desertification in this Republic.

- From 1968 to 1972, the Sudan–Sahelian region experienced the most serious drought disasters in human history, and approximately 200,000 humans and millions of animals were killed during this time.

These lessons are very painful. It is our top priority to avoid the occurrence of such disasters. In China, the situation of desertification is getting worse and hazards caused by desertification are becoming common. The consequences of desertification cannot be ignored, and similar attention should equally be paid to other natural disasters, such as forest fires, earthquakes, and floods. Similar to other hazards, desertification directly weakens the foundation of social and economic development. The final impact and far-reaching threats of desertification are the destruction of the environment and the loss of land resources that humans depend on.

33.12 Summary and Conclusions

Droughts, which in recent years have increasingly intensified due to climate change and desertification, have played an important role in increasing dust. Due to the desertification which resulted in dried soil, smaller particles have been increasing, then they are converted to the form of aerosol; thereby, by wind currents or other physical processes, they join the two airflows. Very small particles are known as the dust. Dust particles contain aerosols (clay and silt). These can be transmitted over long distances and to high altitudes in the atmosphere and ultimately could be deposited in dry or wet form.

Sand and dust storms are natural events that occur widely around the world in arid and semiarid regions, especially in subtropical latitudes. The vast distribution and existence of desert landscapes indicates that these regions were a very important source of dust storms in historical times, but in more recent times the action of humans has created another source on the desert margins in semiarid areas that previously were stable. Major dust storms occur where anthropogenic land disturbances exist in drylands under severe drought. Several areas of the world are contributing to large-scale storms. These areas correspond to areas undergoing accelerated desertification.

Air pollution in Iran has significant natural and anthropogenic sources. The primary anthropogenic sources are industrial activities and transportation, both of which are centered in urban areas, while the main natural source is wind-blown dust.

Iran, like many other Middle Eastern countries, is affected by multiple dust storms each year, especially in the eastern, western, and central regions, which includes Tehran. Such episodes generate high levels of PM, which impairs visibility and causes elevated morbidity.

Dust activity is visible over much of the country for about half of the year, with the activity being the lowest in winter and peaking in May, June, and July. Observations from NASA's TOMS have been used to validate the timing of dust events according to ground meteorological stations in Iran, as well as to characterize primary dust source areas. Data show that the primary sources of dust in Iran are the deserts of the Middle East and Arabian Peninsula, as well as intermittent and dry lakes and marshes, including the Dasht-e-Kavir desert, which includes the Daryacheh-ye Namak salt lake; the Hamun-e-Jaz Murian salt lake; the Hamun/Hamoon lakes and swamps on the Iran–Afghanistan border; and the Al-Hawizh/Al-Azim marshes along the Iran–Iraq border.

Sistan is a region located in southeast Iran with extensive wind erosion, severe desertification, and intense dust storms, which cause adverse effects on regional air quality and human health. For the first time, the mineralogical and chemical properties of dust over Sistan were studied by collecting aerosol samples at two stations established close to a dry-bed lake dust source region, from August 2009 to August 2010. Furthermore, soil samples were collected from the topsoil (0–5 cm depth) at several locations in the dry-bed Hamoun lakes and downwind areas. These data were analyzed to investigate the chemical and mineralogical characteristics of dust, the relevance of inferred sources, and contributions to air pollution. XRD analysis of airborne and soil dust samples shows that the dust mineralogy is dominated mainly by quartz (30%–40%), calcite (18%–23%), muscovite (10%–17%), plagioclase

(9%–12%), chlorite (~6%), and enstatite (~3%), with minor components of dolomite, microcline, halite, and gypsum. XRF analyses of all the samples indicate that the most important oxide compositions of the airborne and soil dust are SiO_2, CaO, Al_2O_3, Na_2O, MgO, and Fe_2O_3, exhibiting similar percentages for both stations and soil samples. Estimates of EFs for all studied elements show that all of them have very low EF values, suggesting natural origin from local materials. The results suggest that a common dust source region can be inferred, which the eroded sedimentary environment in the extensive Hamoun dry lakes is lying to the north of Sistan.

The mineralogy and physicochemical properties of atmospheric particulates were investigated by collecting samples at Abadan (southwestern Iran) near the Persian Gulf coast and Urmia (northwestern Iran) during ambient and dust events for over 6 months (winter 2011; spring 2012). Particle sizes collected were TSP, PM10, and PM2.5. Minerals were identified using XRD; particle morphology and composition were examined by SEM-EDX. Major minerals detected were calcite, quartz, clay minerals, and gypsum, with the relative abundance related to sampling site, collection period, wind direction, sampling head, and total sample amount. The anomalously high calcite content appears as a characteristic feature originated from calcareous soils of the region. SEM observations indicated a wide range of particle morphologies over the 1e50 mm size range, with spherical, platy, cubic, elongate, and prismatic shapes, and rounding from angular to round. Energy-dispersive X-ray analysis of TSP samples from both sites for nondusty periods indicated that the sampled mineral suite contained Al, Mg, Na, Cl, P, S, Ca, K, Fe, Ti, and Si, mostly reflecting calcite, quartz, aluminosilicates, clays, gypsum, and halite. Additionally, As, Pb, Zn, Mn, Sc, Nd, W, Ce, La, Ba, and Ni were detected in TSP, PM10, and PM2.5 samples collected during dust events.

The application and the influence of traditional dust suppression methods, including spraying water, salts, chemicals, and petroleum products on airborne dust particles, are well studied [4,10]. Environmental pollution, hazards, high expense, and fire potential are some of the many disadvantages of these methods. One of the methods that is environmentally safe and satisfies environmental criteria is bio-stabilization or bio-cementation. In the bio-stabilization or bio-cementation process, fine and very fine particles of soil are coagulated by a mineral or an organic agent, which is produced by mosses, liverworts, algae, lichens, fungi, bacteria, or cyanobacteria or any other micro- or macro-organisms.

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34

Drought Management: Current Challenges and Future Outlook

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Abstract The effect of drought on agricultural productivity is widely recognized, but the social, political, and psychological effects of drought may be equally important, especially in a world with increasing urbanization. This chapter discusses the broader aspects of drought and the associated challenges, with a view toward the future in an uncertain world. One of the greatest challenges during the following decades and even centuries is the guarantee of sufficient water supply to all regions of the world. This task is becoming more and more difficult, mainly due to droughts and water scarcity in all continents. First, drought definitions, principles, features, and forecasting and monitoring of droughts and their environmental, economic, and social impacts are discussed. Second, several impacts, including drought vulnerability, impact on urbanization, climate change, agriculture, biotechnology, water contamination, water conservation techniques, and wastewater management, are described. Third, the basic issues of drought management in many areas, including farming, horticulture, urban context, landscape and rural security, crisis management, deficit irrigation, risk mitigation, rainwater harvesting, optimization, and policy-making, are considered.

Drought conditions have spread around the world, namely, in the five continents. An overview of historical drought case studies is presented in the five continents, where Africa is the most affected continent, followed by Asia. This chapter, as the final chapter of the three-volume set, presents the current challenges through the most current developments in the theoretical and practical aspects of forecasting and monitoring droughts, assessing their consequences in many areas, and developing optimal management strategies to reduce or even prevent their negative effects on the environment, economy, and human life. Future outlooks would be defined at the end.

34.1 Introduction

Drought is a regional natural phenomenon with periodic reoccurrence, which can be regarded as an extreme climatic event associated with water resources deficit [45]. The main feature of droughts is a deficiency or lack of precipitation in a region over an extended period. Droughts can occur in both high- and low-rainfall areas and in virtually all climate regimes. Drought is considered as one of the major natural hazards with significant impacts on the environment, society, agriculture, and economy, among others [26]. Specifically, the impacts of droughts may be severe and are neither immediate nor easily quantifiable. It is difficult to determine the effects of drought as it constitutes a complicated phenomenon, evolving gradually in any single region. Indeed, drought impacts are very critical and especially costly, affecting more people than any other type of natural disaster universally [48]. All of this may lead to difficulties in drought assessment and response, which may result in a slow progress on drought preparedness plans and mitigation actions. There is, thus, a need to establish the context in which the drought phenomenon and its associated impacts are described.

Declining water resources in the face of climate changes have become, in many regions of the world, the critical factor to be considered in the elaboration of strategies of local, regional, and global sustainability. Indeed, there are several regions of the world that are characterized as vulnerable areas due to the combined effect of temperature increases and reduced precipitation in areas already coping with water scarcity [45]. As a result, agricultural production risks could become an issue in these regions as mainly droughts are likely to increase the incidence of crop failure. As the complexity of the interactions between climate geomorphology ecosystems and societies increases, there exists an urgent need to deepen the scientific background, first of all to reduce water scarcity, improve water quality, restore biodiversity, and improve ecosystem services and resilience. To achieve this multidimensional goal formulated in the framework of UNESCO International Hydrological Program (IHP) VIII, a two-step strategy has to be developed. The first step involves the identification, distribution, and quantification of drought and pollution risks, and the second one involves the development of innovative methodologies to convert threats into opportunities for sustainability [93].

In terms of climate variability, there is medium confidence that since the 1950s, some regions of the world have experienced more intense and longer droughts [45]. Land-use changes have potential impacts on droughts [5], and anthropogenic forcing has contributed to the global trend toward increased drought in the second half of the twentieth century. Extreme climate variables and climate extremes, such as droughts, are projected to experience significant changes over the twenty-first century, just as they have during the past century, in many areas, including Southern Europe, among others [58,82]. There is also medium confidence that the duration and intensity of hydrological droughts will increase in the twenty-first century in some seasons and areas due to reduced precipitation and/or increased evapotranspiration, although other factors, such as changes in agricultural land cover and upstream interventions, will lead to a reduction in river flows or groundwater recharge. Moreover, climate variability and change may affect drought preparedness planning and mitigation measures [45,69]. Thus, climate change has to be considered in all aspects of drought analysis.

Drought quantification is usually accomplished through indicators and indices. There are several commonly used drought indices based on ground (conventional) and/or remotely sensed data [46,54,108]. Traditional drought quantification methods rely on conventional meteorological data, which are limited in a region, often inaccurate, and usually unavailable in near real time. On the other hand, satellite-based data are consistently available and can be used to detect several drought features and characteristics. Indeed, the growing number and effectiveness of pertinent earth observation satellite systems present a wide range of new capabilities, which can be used to assess and monitor the drought hazard and its effects, such as the drought mitigation activities of the United Nations International Strategy for Disaster Reduction (UNISDR) [91,92]. Moreover, drought monitoring is of critical importance in economically and environmentally sensitive regions and provides very significant inputs in any drought preparedness and mitigation plan.

This chapter provides a synthesis of the recent state of knowledge on droughts, which has been fundamental to the development strategies and methodology for achieving a sustainable future. It also draws a general overview on drought management planning in face of current natural and socioeconomic challenges, as well as drought historical case studies in the five continents. At the end, drought perspectives and future outlooks are considered.

34.2 Drought Concepts and Features

Drought indicators are variables that describe drought features. Several indicators can also be combined into a single quantitative indicator, namely, a drought index [102]. For monitoring drought, drought indices are used based on several drought features, such as severity, duration, onset, end time, areal extent, and periodicity [28]. Moreover, for drought assessment through drought indices, the focus is on the estimation of precipitation shortage and water supply deficit; however, evapotranspiration or temperature may also be included [84,97].

Since the last decade, a web services–based environment is being developed for integration of regional and continental drought monitors; for computation and display of spatially consistent systems, such as in situ Standardized Precipitation Index (SPI), satellite-based indices and modeled soil moisture; and for drill-down capacity to regional, national, and local drought products. This is an ongoing applied research effort, which has indicated, among others, the research need for composite drought indices (CDIs) toward a global drought risk modeling system [14,108] based on remote sensing data and methods. Indeed, due to the complexity of drought, the scientific trend and research need is to consider multiple indicators or CDIs for assessing and monitoring droughts [39]. There are indices for all types of drought, although there is no “one-size-fits-all” drought index or indicator. In summary, the approaches to drought assessment are essentially three [80]: (1) single indicator or index (parameter), (2) multiple indicators or indices, and (3) composite or hybrid indicators, which integrate several indicators or indices as a "Convergence of evidence" approach. Furthermore, drought preparedness and mitigation planning based on remote sensing data and methods is considered an essential component of integrated water resources management. It is recognized that there is an international research need for drought preparedness plans through the development of decision support systems (DSS) [27,101]. It is also recognized that the drought policy principle has to consider the implementation of preparedness and mitigation measures [5,100].

Drought is not just a physical phenomenon, because it results from an interplay between a natural event and demands placed on the water supply by human-use systems. Indeed, there is no universally accepted definition of drought, since there are a wide variety of sectors affected by drought, as well as due to its diverse spatial and temporal distribution [41]. More than 150 published definitions of drought have been identified [60]. If drought is considered as a phenomenon, it is certainly an atmospheric phenomenon. Nevertheless, by considering drought as a hazard, there is a tendency to define and classify it into different types; however, the relationship between the different types of drought is complex. In the international literature, three operational definitions are considered, namely, meteorological or climatological, agrometeorological or agricultural, and hydrological drought [102]. As a fourth type of drought, the socioeconomic impacts of drought can also be considered. All droughts begin with a deficiency of precipitation in a region over a period. These early stages of accumulated departure of precipitation from normal or expected are usually considered as meteorological drought [25]. A continuation of these dry conditions over a longer period, sometimes in association with above-normal temperatures, high winds, and low relative humidity, quickly results in impacts on agricultural and hydrological sectors. Specifically, with the exception of meteorological drought, the other types of drought emphasize on the human or social aspects of drought, in terms of the interaction between the natural characteristics of meteorological drought and human activities that depend on precipitation.

34.2.1 Factors and Drivers

Several factors may be implicated as potential causes of drought: ENSO (El Nino Southern Oscillation), abnormal sea surface temperature (SST) patterns in areas other than the equatorial eastern Pacific, soil moisture desiccation, and nonlinear behavior of the climate system. Frequent droughts around the world, and interest in their possible links with phenomena such as El Nino, keep the hazard in evidence even for the casual observer. Drought impacts refer to a multitude of drivers that may turn physical drought causes, such as reduced average precipitation, deficient soil moisture, and low water levels, into disaster events for vulnerable populations and economies. Some apparent disaster trends are attributed to socioeconomic factors rather than to the frequency and magnitude of geophysical processes. There are certainly several causes and drivers that justify the increasing trend in disaster impact, despite the fact that the frequency of geophysical events remains almost the same and there are many positive efforts to reduce disasters [26]. These types of drought risk causes and drivers may include land pressure, climate change, economic growth, technological innovation, population growth, urbanization, inequalities, political change, social expectations, risk governance capacities, and global interdependence, among others. A very brief description of the main drought risk drivers is outlined next, which constitutes a current research subject due to its global significance.

34.2.2 Climate Variability/Change

The main effect of increasing climate variability and/or change is temperature increases and precipitation reductions in several climate zones around the world [10]. Climate scenarios indicate an increase in the reoccurrence interval of droughts, leading, for example, to significant crop losses or even failure, as well as impacts on small-scaling farming ([20,23]).

34.2.3 Land Pressure

A portion of the world's population (about 20%) lives in areas suffering severe environmental degradation, with the majority depending on agriculture. In such cases, rural land pressure, in terms of inappropriate water and soil management, constitutes a drought risk driver. Typical examples are water-intensive crops, soil erosion, shifting production patterns, deforestation, as well as overgrazing and rangeland management.

34.2.4 Population Growth and Inequality

The world population is steadily increasing; thus, the number of people exposed to hazards is equally increasing, since about 90% of the population growth takes place in the less developed countries, which face high human vulnerability. Similarly, disaster vulnerability is closely associated with the economic gap between rich and poor. Indeed, poverty and rural vulnerability constitute drought risk drivers, which may result, for example, in a lack of irrigation and water storage, as well as in expansion of intensive cash crop production.

34.2.5 Urbanization and Economic Growth

Urban and economic development is seldom planned to take adequate measures for water management and conservation. This results in increasing water demand for various sectors, such as intensive agriculture, urban development, tourism, and other economic sectors, which constitutes both agricultural and hydrological drought risk drivers. *Weak risk governance capacities* are a drought risk driver. There is a need to develop national drought risk management policies, to assign high priority to drought, to avoid fragmented responsibilities for drought risk management at local or regional level, to establish drought insurance compensations, and to avoid conflict and excess water use. Technological innovations may be helpful in drought forecasting and early warning, as well as in seasonal climatic forecasting.

34.2.6 Drought Features

For assessing and monitoring droughts, several drought features are usually detected [25,54]. A description of some key features follows:

Severity: Severity or intensity of drought is defined as escalation of the phenomenon into classes from mild, moderate, and severe to extreme. The severity is usually determined through drought indicators and indices, which include these classes. The regions affected by severe drought evolve gradually, and there is a seasonal and an annual shift of the so-called epicenter, which is the area of maximum severity.

Periodicity: Periodicity is considered the recurrence interval of drought.

Duration: Duration of a drought episode is defined as the time interval between the start and the end time, usually in months.

Onset: The beginning of a drought is determined by the occurrence of a drought episode. The beginning of a drought is assessed through indicators or indices reaching a certain threshold value.

End time: End time of a drought episode signifies the termination of drought based again on threshold values of indicators or indices. Since drought is a complex phenomenon, it is often difficult to determine the onset and the ending of a drought and on what criteria these determinations should be made.

Areal extent: Areal extent of drought is the spatial coverage of the phenomenon as is quantified in classes by indicators or indices. Areal extent varies in time, and remote sensing has contributed significantly in the delineation of this parameter by counting the number of pixels in each class of drought.

34.3 Current Drought Challenges

Drought poses several challenges, which can be distinguished into natural and physical, as well as into socioeconomic challenges. A brief presentation follows.

34.3.1 Natural and Physical Drought Challenges

Drought has significant impacts on several natural and physical processes and phenomena, namely, dust storms, wildfires, sedimentation, heat waves, desertification, water quality, climate change, as well as landscape. A brief description follows.

34.3.1.1 Dust Storms

Sand and dust storms are natural events that occur widely around the world in arid and semiarid regions [75]. Major storms occur when prolonged drought and lack of precipitation in a region over an extended period cause the soil surface to lose moisture [76], although plant cover reduces wind velocity at the soil surface and soil moisture improves cohesion between individual soil particles. Drought and wind contribute to the emergence of dust storms, with local, regional, and global implications toward global warming, land degradation, and desertification [73]. Moreover, heavy metals can cause serious human health problems, since they can accumulate in the human body, with a relatively long half-life [61]. Dust storms impact on source, transport, and deposition environments, affecting soil fertility and, thus, resulting in a loss of agricultural productivity. During dust transportation, there is significant reduction in visibility, which could range from a slight haze to a major dust cloud. This loss of visibility can be a major hazard to aircraft and, in some cases, to motorists. In addition, mineral dust plays an important role in the supply of nutrients and micronutrients to oceans and terrestrial ecosystems [64]. Dust cloud contributes to air pollution in populated areas [55,99]. Drylands around North Africa and the Arabian Peninsula are the main terrestrial sources of airborne dust. Moreover, contributions from Iran, Pakistan, and India to the Arabian Sea, and China's significant storms, deposit dust in the Pacific. It is stated that poor management of the Earth's drylands, such as neglecting the fallow system, causes an increase in dust storms' size and frequency from desert margins and affects both the local and the global climate, with an additional impact on local economies [75]. Research results of the Geology Faculty of Oxford University, United Kingdom, show that Great Britain has suffered dust storm disasters 17 times since 1900 and about 10 million tons of dust particles is transported to the United Kingdom from the Sahara desert during a single dust storm event.

34.3.1.2 Wildfires

During drought events, there is an increased risk for wildfires and dust storms. Also, drought and lack of water can cause many natural hazards, including wildfires, photochemical reactions, volcanic eruptions, and erosion. Moreover, heat and low moisture cause climate change and an increase in bushfire frequency. Wildfires can cause desertification when drought events occur in a region where the temperature is high. Wildfire and dry soil and vegetation increase the number of particulates suspended in the air, such as pollen, smoke, and fluorocarbons. These substances are able to irritate the bronchial passages and lungs, making chronic respiratory illnesses such as asthma worse. This can also increase the risk of acute respiratory infections such as bronchitis and bacterial pneumonia. Other drought-related factors involve the presence of airborne toxins originating from freshwater blooms of cyanobacteria, which can become airborne and have been associated with lung irritation [64,72,98]. In Australia, during drought events, bushfires may become widespread and hazardous, causing significant economic loss. The Black Friday fire of 1939 and the Ash Wednesday fire of 1983 are the two most devastative bushfires in Australia's history [50]. However, the deadliest fires in Australian history took place in 2009, where dry conditions and extreme heat wave prevailed; around 4000 homes were burnt in Victoria, and 173 deaths and 414 injuries were reported during the fires, known as Black Saturday bushfires [67]. Just 1 week before the fires, Melbourne experienced three continual days of extreme high temperatures (above 43°C), with a record of the third hottest day in the city's history of 45.1°C.

34.3.1.3 Sedimentation

Low flow is a characteristic of hydrological drought with seasonal periodicity occurring usually toward the end of summer or beginning of fall. Sediments that produce erosion are carried by the water flow; however, the rate of sediments density and muddy water in rivers is typically small [62]. The possible environmental effect due to low streamflow is the decrease in water quality. An increase in water pollution, sedimentation, and elevating water temperature lead to an unhealthy riverine ecosystem. The reduction in deltas, which are important agricultural areas for inhabitants, mostly due to the fertile soil, results in sediment reduction. There are several factors contributing to sedimentation, such as climate, geology, soil, hydrology, physiography, as well as human activities [88,90]. The contributing nonclimate factors include deforestation, land degradation, land-use change, irregular grazing, and improper irrigation. Specifically, land degradation is characterized by changes in the physical, chemical, and biological soil properties, which lead to erosion, loss of its productivity ability, and, most of the time, to desertification [87]. Soil particles are separated by rainfall or surface runoff and characterize water erosion, which is more important in humid or semihumid regions [4]. There are natural and human factors that affect streamflow. The natural factors depend on climate, physiographic characteristics, geology, land use, and storage characteristics [77]. The human factors, such as water abstractions for industrial, agricultural, and domestic use; urbanization; land-use changes; and decrease in the amount of water in rivers, affect mainly the dry season and its frequency [96]. Four categories of environmental flow assessment methodologies are considered, such as hydrological, hydraulic rating, habitat simulation, and holistic methodologies. These methodologies can be combined with other approaches to provide improved water management solutions under low-flow conditions.

34.3.1.4 Desertification

There are several factors contributing to desertification, such as climate, geology, soil, hydrology, physiography, biology, as well as socioeconomic and human activities [88]. Desertification can be characterized as physical or chemical depending on the processes involved. Specifically, physical degradation occurs on sloping lands and is very extensive, where the dominant physical process is accelerated soil erosion, which occurs on marginal lands that have lost more than 60% of their vegetation cover and are located within semiarid and dry subhumid zones. In addition, the dominant process of chemical desertification is secondary salinization of soils through irrational water management in irrigated lands. Desertification occurs as a result of a long-term failure to balance human demand for ecosystem services and the amount the ecosystem can supply [42]. These services include provisioning services such as food and water; regulating services such as flood and disease control; cultural services such as spiritual, recreational, and cultural benefits; and supporting services such as nutrient cycling that maintain the conditions for life on the Earth. Plant cover and biomass production, as well as the disruption of food production systems, measure the impact of drought on natural ecosystems. Decertified soils are subject to extensive water and wind erosion and therefore lose much of their depth and ability to store water and nutrients. Overgrazing results in the redistribution of organic matter, and nutrients may be the primary agent responsible for the current conversion of previously productive grasslands to unproductive shrublands [70]. Desertification differs from drought. Yet desertification and drought are concurrent for the long run destroy of the all-important resource base on which an ever-growing population must increasingly depend. There are a few other environmental issues that deserve global attention, such as the impacts of drought and desertification, which add to the life-threatening pressures on inhabitants of drought-prone regions.

34.3.1.5 Heat Waves

The term heat wave refers to unusually high temperatures. Specifically, if heat lasts for several days or longer, it is called a heat wave. Heat waves are embedded in the usual course of summer weather. Drought episodes with extended areal coverage and extensive duration and severity, combined with high temperatures, result, among others, in disastrous heat waves and/or extensive wildfires. Indeed, the succession of abnormally dry years can have disastrous environmental, economic, and social effects. Moreover, in subtropical climates, such as the Mediterranean region, most fire incidents occur during midday, when the daily temperature and relative humidity are at their maximum [85]. Similarly, hot days are common in many parts of the world, but a succession of very many hot days can lead to disastrous heat waves, especially in areas not normally accustomed to heat waves combined with high humidity. Moreover, the destruction of vegetation by wildfires can have effects on the soil surface and the hydrological cycle through an increase in albedo, surface runoff, a reduction in evapotranspiration, an increase in erosion, and the presence of floods and desertification. Furthermore, gases released by the burning of biomass can contribute to the greenhouse effect and cause destruction of the ozone layer.

34.3.1.6 Water Quality

The quality of water is a measure of its purity in terms of soluble compounds, both organic and inorganic in nature, with certain chemical properties such as pH and alkalinity, and in terms of inorganic and organic particulates suspended in the water. Ash is rich in phosphate and nitrate, where the latter is much more soluble and remains in waterways for up to a decade after the drought itself has terminated. Levels of nitrate in receiving waters can exceed the maximum contaminant level of 10 mg nitrate/L set by the U.S. Environmental Protection Agency. Phosphates are not as soluble in water and are less harmful most of the time; however, phosphate is the limiting nutrient for nitrogen-fixing cyanobacteria (blue-green algae). Thus, a small amount of this nutrient can have significant effects on the receiving waters [87]. The effect of wildfires on water quality of local rivers, lakes, and streams is usually experienced once rainfall begins after the fire has been quenched. Certainly, wildfires occur during on-drought periods, but since drought does exacerbate wildfire frequency, these kinds of events must be considered as a special case by water supply managers and public health officials, who must maintain vigilance once droughts are evident [94,95]. Moreover, water quality issues must be addressed during and especially after a drought ends. Specifically, following a drought, rainfall is often much greater than normally expected and nutrients, especially phosphates and nitrates, along with sediments, wash into water bodies and some precipitation leaches into the groundwater. A reduction in the pH and acid-neutralizing capacity of the water can liberate metals such as aluminum from the bedrock.

34.3.1.7 Climate Change

The main focus of climate change is on energy policy and greenhouse gas emissions, and less attention is paid to the implications of climate change impacts, such as water scarcity and water quality risks [56]. The high population density in urban areas, with considerable water demand in these regions, constitutes an issue, since urban water deficit is a common problem around the world, especially in arid and semiarid regions. Climate change impacts could intensify water shortage in urban areas. The water demand would increase due to global warming, whereas water resources could be limited [44]. Climate change might result in wetter or drier climates in different regions. However, it seems that water stress and drought frequency and intensity would increase in the future, especially in developing countries, as a result of climate change.

Population growth highly increases global food and water demand. Further, the change in climate variables, global warming will affect water demand, especially in the agriculture sector as dominant water consumer. The increase in domestic, industrial, and environment water demand would be intensified as a result of climate change, even though technological developments could help in managing water demand, especially in industry. The development of resilient water supply strategies could highly help in the mitigation of adverse impacts of climate change [35]. With climate warming conditions, not only is the severity of drought episodes driven by precipitation, but also the atmospheric evaporative demand (AED) is gaining importance. Indeed, global warming could cause an increase in vapor pressure deficit, which contributes to increased land aridity and triggers extreme drought events. The AED is necessary for the evolution of drought severity, since the development of water resources, observed desertification processes, and the enhanced frequency of forest dieback episodes cannot be explained just by the evolution of precipitation. The conclusions of several regional studies are that the severity of drought may be increasing in recent decades as a consequence of global warming [79].

34.3.1.8 Landscape

Water scarcity and drought in many densely populated regions of the world have urged the development of more efficient and water-wise communities for successful urban landscapes. Urban lands are expected to triple by 2030, which results in about 1.4% of land cover being occupied by urban areas [71]. Therefore, urban green landscape is considered one of the important elements of a sustainable city. The identification and introduction of endemic drought- or water stress–tolerant plant species with acceptable aesthetic values into the urban landscape should be put on the agenda of research and urban management based on different climatic zones and geographical conditions. The integrated adoption of new technologies could be done in the context of the ever-expanding knowledge about nature and should be considered as a practical strategy to tackle the existing and emerging challenges in human societies and nature.

34.3.2 Socioeconomic Drought Challenges

Drought has significant impacts on several socioeconomic issues and aspects, such as health issues, economic loss, social aspects, water security, as well as food security. A brief description follows.

34.3.2.1 Health Issues

Sanitation is a necessity for a healthy life and has posed a challenge to most parts of the world, especially in the developing countries. Hazards from poor sanitation can be physical, microbiological, biological, or chemical in nature. Many of these hazards can be naturally occurring or are components emanating from wastes generated by human activities. Wastes that can cause health problems include human and animal excreta, solid wastes, domestic wastewater (viz., sewage, sewerage, gray water), industrial wastes, and agricultural wastes [11]. The life cycle and activities of these hazardous vectors are affected due to changes in seasonality, rainfall patterns, and wind, and these observations underscore the necessity to include sanitation strategy as part of drought mitigation programs within drought policies [36]. Drought causes an increased public health challenge. Moreover, the relationship between water quality and quantity is complex; however, both are necessary for good health, since water discharge and water levels associated with droughts are typically low [72].

34.3.2.2 Economic Loss

The effects of drought on micro- and macro-level economy can also be classified into direct and indirect impacts [18,108]. Indirect impacts of drought are generally severe and consequential compared with direct impacts, since drought first affects the agricultural sector, which is the foundation of the economy in most of the developing and least developed countries [105]. Estimation of indirect impacts of drought is more complicated due to a lack of theoretical and methodological foundations [20]. Indirect negative impacts of drought also include increased import of certain goods due to the shortage of local supplies and healthcare cost from malnutrition. Decreased water level and impaired navigability in rivers, lakes, and canals enforce alternative transportation, which always results in elevated marketing costs.

Drought is one of the worst natural disasters that affects local economy badly. In the world history, in terms of death, drought is at the top in terms of human casualty and livestock and other animal death. For example, from 1896 to 1902, approximately 6 million people died in India due to a famine, mainly caused by drought. From 1959 to 1961, droughts in Northern China resulted in a famine that killed more than 30 million people. In Australia, the Millennium Drought has impacted the agricultural employment sector significantly, which was large enough to affect employment and the economic growth. It was reported that around 100,000 jobs were lost in the agricultural sector during the 2002–2003 period as a direct effect of the drought [6]. Around 10,636 families left farming from 2001 to 2006 during the drought period. Moreover, many other farm families took employment in other sectors to bear the living expense [17]. An increase in food prices of many items, such as fresh vegetables, is generally experienced during drought periods due to reduced production [7]. Some countries are prone to droughts and face acute poverty at the household as well as at the community level [104]. Drought forecasting is a critical component of drought assessment, which plays a major role in risk management, drought preparedness, and mitigation.

34.3.2.3 Social Aspects

Social perspective is important, since land use may lead to changes in water demand or alter the water storage capacity of ecosystems, leading to more frequent or more severe dry spells and droughts [53,103]. Some societies suffer from permanent water stress or scarcity in arid and semiarid regions of the world. Human societies are also affected by drought occurrence indirectly due to the increase in the amount of greenhouse gases in the atmosphere, which leads to warming, higher potential evapotranspiration, and changes in global circulation, affecting the distribution of precipitation on the Earth [43,83]. Moreover, drought and water scarcity affect people directly due to the reduction in the amount of safe drinking water and waterborne sanitation possibilities, which lead to increased health and morbidity risks. They also harm food production by reducing the water available for rainfed and irrigated crops [81]. In addition, drought may reduce breeding sites of mosquitoes hosting malaria parasites [38]. According to the United Nation Millennium Development Goals (UN MDG) Report 2015 [19], there are still many regions of the world that have not met the goal (e.g., Oceania and Sub-Saharan Africa) of access to safe drinking water. It was estimated that globally 663 million people lacked access to improved water sources in 2015, the proportion being larger in rural than in urban areas [86]. According to basic human water requirements defined by Gleick [37], each person needs 50 L of water for basic drinking, hygiene, sanitation, and food preparation purposes per day. According to the Falkenmark Index, 1700 m^3 of water per inhabitant is considered the limit of *water stress* in an average year, whereas the threshold for *water scarcity*, below which life and food production systems are endangered, is set as 1000 m^3 of water per inhabitant per year [32].

34.3.2.4 Water Security

Human activities adversely affect the water bodies of the planet. The worldwide demand for water is increasing. The degree of availability of clean drinking water and technical issues have an impact on economic and social development. Water pollution is considered as a part of the constant threats to the security of water on a local, regional, and global level. According to estimates by the International Bank, more than 1 billion people lack access to clean water, 40% of the world experiences water shortages, and 3 billion people live in unsanitary conditions. Approximately 80% of infectious diseases are transmitted through water annually, claiming the lives of millions of children. Forty percent of deaths in the world are caused by water pollution. Water pollution leads to the fact that people absorb toxic substances through drinking water or water used for irrigation of agricultural food products [37]. Black Sea, Aral Sea, Dniester and Prut rivers, Lake Urmia, and Lake Sevan are a few examples.

There is research evidence on the harmful effects of man-made pollution on human health. Potentially, the highest risks to the environment and, in particular to water, are nuclear facilities, chemical and petrochemical industries, pipelines, and transport. These risks occur every day and are no less dangerous, but not eye-catching technological effects, which arise from air emissions that pollute not only the air, but also cause pollution of atmospheric precipitation, reservoirs, and rivers. Moreover, landfill hazardous wastes pose a potential threat to groundwater. Their evil is the gradual and imperceptible accumulation of harmful substances, which inevitably threaten nature and humans.

Droughts are global environmental events that are experienced by large numbers of people around the world. Droughts affect many aspects of human activities. The study of anthropogenic droughts suggests that as humans impact global weather patterns and climate change occurs, the lessons learned in earlier droughts may not be applicable. Humans play a significant role in determining the severity, duration, and impacts of drought phenomenon. At the same time, humans are now more capable of adapting to and mitigating droughts [2]. Indeed, many different factors affect how the authorities and population respond to drought. Some climate models make direct predictions, as they project increased aridity in the 21st century over most of Africa, southern Europe and the Middle East, most of the Americas, Australia, and Southeast Asia. Regions such as the United States might witness persistent droughts in the next 20–50 years [22]. Therefore, a UN report [45] lays out a framework for drought risk reduction that is anchored in the following steps: (1) policy and governance, (2) drought risk identification and early warning, (3) awareness and education, (4) reduction in background drought risk factors, and (5) mitigation and preparedness. Drought early warning detection systems involve monitoring certain indicators that are associated with the major effects of lower rainfall, as well as socioeconomic indicators, such as the vulnerability of food production systems, food security, availability and access to drinking water, access to fodder for livestock, food prices, and population migration patterns and trends [29].

34.3.2.5 Food Security

Food security is defined as a situation that exists when all people, at all times, have physical and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life [35]. The human population has been gradually increased from 2 to 20 million when agriculture has settled about 12 million years ago to 7.2 billion in 2013, which is expected to reach 9.6 billion by 2050 and 11 billion by 2100 [89]. On the other hand, global food production must be increased by 50%. Certainly, the global natural resources are playing a potential role in food production, economic development, and the balance of natural ecology [33–35,89]. The contemporary engineering technology for agricultural practices and natural resources usage should be based on current drought, water scarcity, and environmental harsh conditions. The innovation of modern approaches for climate-smart agriculture and nutrition policies would lead to optimal solutions globally toward protecting traditional agricultural products and ensure food security [1,3,44].

Similarly, the world's forests are the most important natural resource frequently used in different regions of the world. It is estimated that 31% of the world's surface area represents forest resources [35]. Soil development and fertility improvement depend on the water supply and quality of surface and groundwater storage. In cold climate regions, during the last two decades, there has been evidence of growing water stress, in terms of both water scarcity and quality deterioration. Moreover, by 2020, water use and reuse are expected to increase by 40%, and 17% more water will be required for food production to meet the needs of the growing population. By 2025, 1.8 billion people are expected to live in regions with absolute water scarcity. Moreover, about two-thirds of the world population could be living under water, agriculture, and natural resources stress [3]. Therefore, sustainable use of agricultural practices, including water, soil, forest, air, oil, gas, and petroleum mining sectors, should be considered within a strategic management approach in food production. For analytical purposes, the complex definition of food security can be broken up into three components: availability, access, and utilization. A fourth dimension, stability, refers to the requirement that food-secure people have access to appropriate food at all times [31].

34.4 Global Drought Conditions

Drought is undoubtedly the most far-reaching of all natural disasters. From 1991 to 2000 alone, drought has been responsible for over 280,000 deaths and has cost tens of millions of US dollars in damage. For example, Sub-Saharan Africa suffered its worst dry spell of the century in 1991–1992 when drought covered a region of 6.7 million km^2 and affected about 110 million people. After a relatively quiet year in 1999, in 2000, there have been a series of extreme droughts in certain regions of the world. The country of Georgia, a former republic of the USSR and now a member of the Commonwealth of Independent States, which produces excellent varieties of grapes for wine making and produces grains and vegetables, was hit by an unusually intensive drought. In addition to Georgia, North America, Sub-Saharan Africa, and Southeastern and Central Asia were among the regions of the world most seriously affected. Severe vegetation stress has been persisting, since spring around and south of the Caspian Sea, Western India, most of Mongolia, and adjacent areas of China. In the Horn of Africa, nearly 15 million people were affected from unusual droughts, which resulted in crop failures earlier this year in Ethiopia. Nearly 60% of Kenya was affected by extreme droughts, the largest area affected since 1991. Afghanistan and Pakistan had severe vegetation stress due to a lack of precipitation and excessive heat since mid-February. In the United States, in addition to crop and pasture failures in the southeastern and central states, drought caused large areas of intensive fires in the northwest.

By the year 2025, the world population projected to be living in water-scarce countries is expected to rise to between 1.0 billion and 2.4 billion, representing roughly 13%–20% of the projected global population. Africa and parts of Western Asia appear to be particularly vulnerable to increasing water scarcity. The fight against drought receives a high priority in the World Meteorological Organization (WMO), which involves National Meteorological and Hydrological Services in regional and subregional cooperative projects, such as the operation of Drought Monitoring Centres in Africa (DMC-Nairobi, DMC-Harare). In particular, the WMO promotes research on the interactions between climate, the hydrological regime, and drought in the context of climate variability, change, and water resources scarcity. With a view to developing appropriate response strategies, the WMO's efforts in drought forecasting and mitigation are supplemented by public awareness and education. For illustrative purposes, Table 34.1 presents the number of different natural disasters per country within each of the five continents for a period of 15 years (1991–2005) International Strategy for Disaster Reduction (ISDR). For instance, from Table 34.1, it can be seen that the highest number of drought episodes occur in Africa, followed by Asia. Similarly, Figure 34.1 shows the global map of the distribution of a widely used agricultural drought index, namely, the Vegetation Health Index (VHI), for January 22, 2007 (third week), in which such maps are issued weekly. A description of drought occurrences and characteristics per continent follows.

34.4.1 Drought in Africa

The majority of droughts in the world have occurred in Africa. Indeed, drought is a condition of life for many residents of Africa, especially those of the Greater Horn region. The countries in Africa reporting the highest frequency of drought include Ghana, Burkina Faso, Mauritania, Zimbabwe, Ethiopia, and Mozambique. For example, as already mentioned, Sub-Saharan Africa suffered its worst dry spell of the century in 1991–1992 when drought covered a region of 6.7 million km^2 and affected about 110 million people. In Figure 34.2, Normalized Difference Vegetation Index (NDVI) anomaly for Africa is shown for August 2000 (Figure 34.2a) and 1984 (Figure 34.2b) calendar years. The NDVI anomaly images are produced by comparing a specific month (e.g., August) or the year's NDVI data with the 20-year average to reveal whether the productivity in a given region is typical, or whether the plant growth is significantly more or less productive. Dark reddish-brown areas indicate unhealthy vegetation relative to a normal year. The drought withered crops from the Sahel (along the southern border of the Sahara desert) to East Africa and hit Ethiopia, Sudan, and Somalia especially hard. Roughly 800,000 people died during the resulting famine of 1984.

Thousands of people are affected or killed by drought in Africa (Figure 34.3). The single worst drought disaster killed 300,000 people in Ethiopia in 1984 (Table 34.2) and affected 14.3 million people

TABLE 34.1 Number of Natural Disasters by Type: Regional Distribution from 1991 to 2005 (ISDR)

	Hydrometeorological Disasters							Geological Disasters			Biological Disasters			
	Drought	Extreme Temperature	Flood	Slide	Wildfire	Wind Storm	Total	Earthquake and Tsunami	Volcano	Total	Epidemic	Insect Infestation	Total	Total
Africa														
Eastern Africa	87		132	7	2	46	274	11	3	14	146	3	149	437
Middle Africa	8		37	2	2	1	50	1	1	2	50	2	52	104
Northern Africa	9	6	56	2	2	9	84	12		12	19	2	21	117
Southern Africa	23	1	24	1	7	17	73	2		2	12		12	87
Western Africa	18	2	87	2	2	15	126		1	1	151	8	159	286
Subtotal	145	9	336	14	15	88	607	26	5	31	378	15	393	1031
Americas														
Caribbean	6		44	2	2	95	149	5	4	9	6		6	164
Central America	20	13	82	12	7	76	210	31	19	50	30		30	290
North America	8	11	90	1	56	236	402	10	1	11	9		9	422
South America	23	21	165	46	20	36	311	34	10	44	28	3	31	386
Subtotal	57	45	381	61	85	443	1072	80	34	114	73	3	76	1262
Asia														
Eastern Asia	31	8	132	34	8	219	432	81	5	86	17	1	18	536
South Central Asia	22	47	285	63	7	137	561	95		95	103	4	107	763
South East Asia	25		198	47	13	140	423	56	23	79	61	1	62	564

(*Continued*)

TABLE 34.1 (*Continued*) Number of Natural Disasters by Type: Regional Distribution from 1991 to 2005 (ISDR)

	Hydrometeorological Disasters							Geological Disasters			Biological Disasters			
	Drought	Extreme Temperature	Flood	Slide	Wildfire	Wind Storm	Total	Earthquake and Tsunami	Volcano	Total	Epidemic	Insect Infestation	Total	Total
Western Asia	13	11	57	7	5	23	116	38		38	12		12	166
Subtotal	91	66	672	151	33	519	1532	270	28	298	193	6	199	2029
Europe														
Eastern Europe	7	46	108	10	23	47	241	12		12	19	1	20	273
Northern Europe	2	12	22	2		27	65	2	1	3	6		6	74
Southern Europe	9	19	70	5	25	20	148	22	2	24	10		10	182
Western Europe	1	19	60	6	3	38	127	5		5	6		6	138
Subtotal	19	96	260	23	51	132	581	41	3	44	41	1	42	667
Oceania														
Australia	6	5	36	2	11	49	109	1	1	2	2	2	4	115
Melanesia	5		9	5	1	24	44	11	9	20	5		5	69
Micronesia	2					10	12	1		1	2		2	15
Polynesia	1			2		16	19	1		1	2		2	22
Subtotal	14	5	45	9	12	99	184	14	10	24	11	2	13	221
Total	326	221	1694	258	196	1281	3976	431	80	511	696	27	723	5210

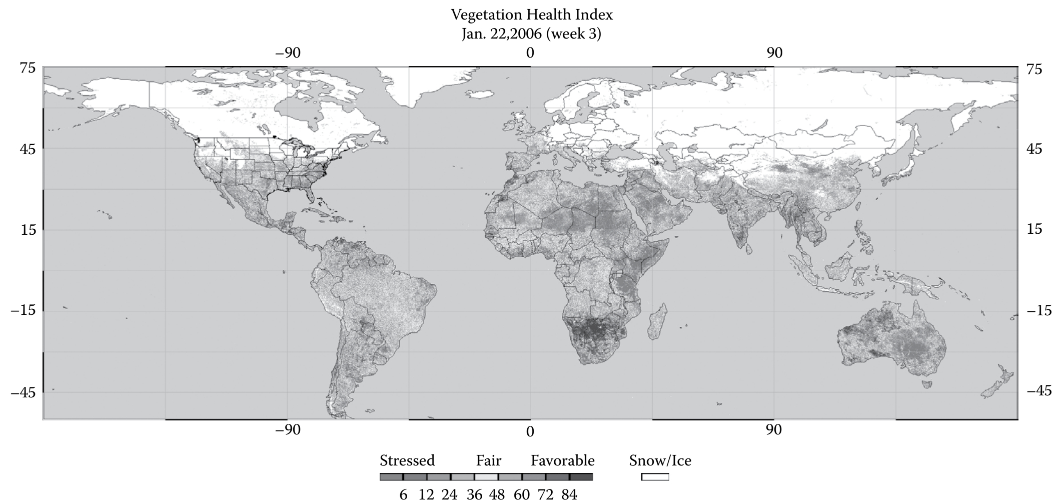


FIGURE 34.1 Global Vegetation Health Index distribution for January 22, 2007 (third week).

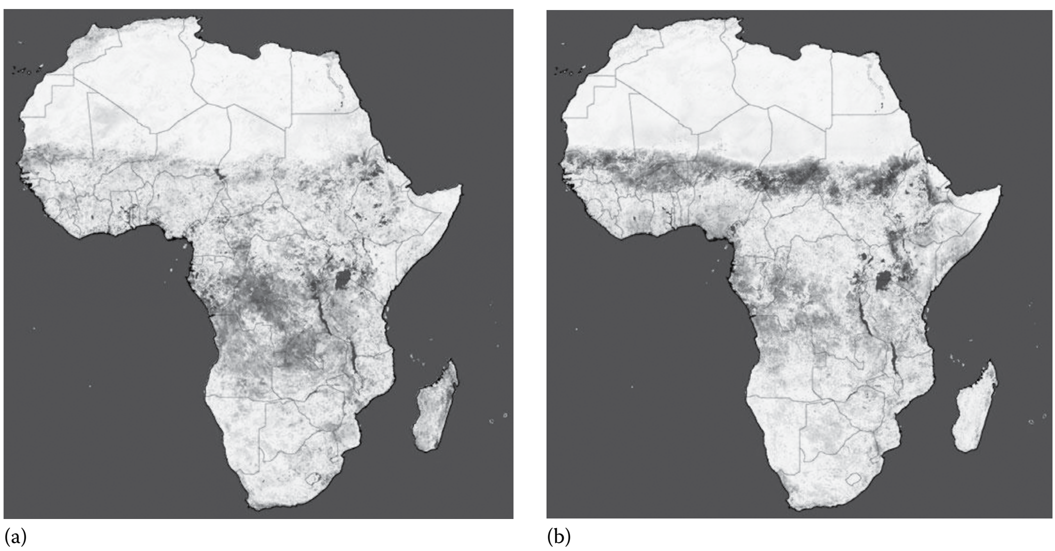


FIGURE 34.2 NDVI anomaly in Africa: (a) August 2000 and (b) August 1984.

in 2002. In economic terms, the cost of droughts in Africa is enormous. For example, the economic impacts of the 1991–1992 drought in Southern Africa included a GDP (gross domestic product) reduction of $3 billion, reduced agricultural production, increased unemployment, created heavy government expenditure burden, and reduced industrial production due to curtailed power supply. A decade later, the 1992–2001 La Niña–related drought in Eastern Africa cost the Kenya economy alone about $2.5 billion.

34.4.1.1 Ghana

Most affected provinces: upper and northern regions. Ghana, which was almost self-sufficient in cereal production several years before drought, faces a severe economic and financial crisis aggravated by the prolonged drought. The marked deterioration in agricultural production, compounded by the nonavailability

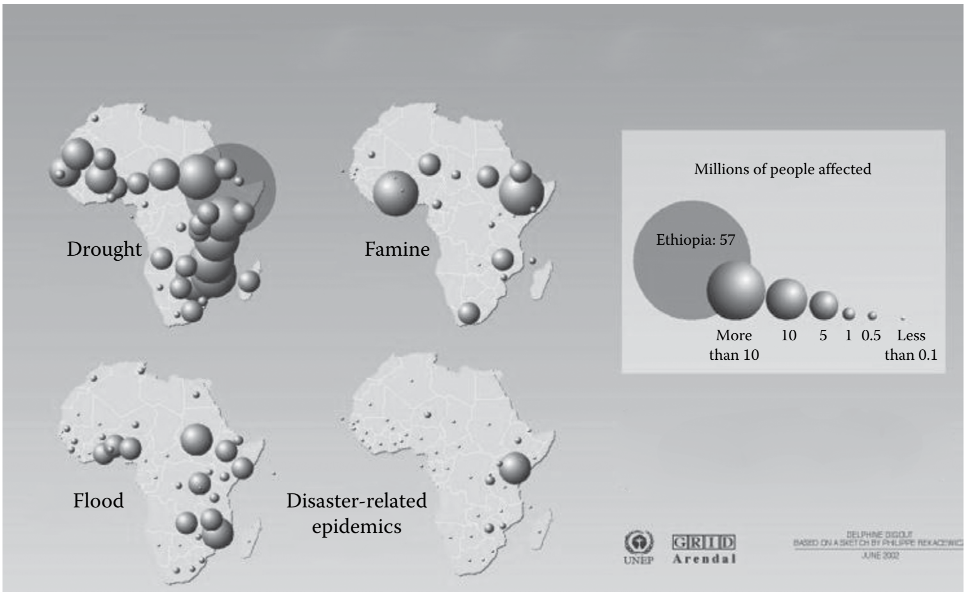


FIGURE 34.3 People affected by natural disasters in Africa, from 1971 to 2000. (From The Office of U.S. Foreign Disaster Assistance (OFDA), The Center for Research on the Epidemiology of Disaster (CRED), International Disaster Database, Université Catholique de Louvain, Brussels, Belgium, www.cred.be/emdat, accessed on July 22, 2016.)

of transport and fuel, the poor road network, the lack of storage facilities, and a reduced purchasing power, has had immediate impacts on the nutritional status of mothers and children. The infant mortality rate, which was steadily diminishing, is on the increase throughout the country and especially in the north. Food shortage is especially dramatic in the northern part, since a serious logistic problem has to be overcome to facilitate food distribution in this region.

34.4.1.2 Burkina Faso

Most affected region: the northern part of the country (Sahel region). Burkina Faso, formerly Upper Volta, the fifth poorest country in the world, with one of the highest infant mortality rates, has been seriously affected by drought and desertification ever since 1968. The lowest recorded rainfall for 30 years was registered in 1981 when about one-third of the country's livestock was lost due to drought. Similarly, 1983 was another peak drought year, especially in the northern part of the country, where the harvest failed completely. In a country where the health and nutrition status of children and mothers is normally already very poor, drought renders them even more vulnerable to communicable and parasitical diseases as malnutrition increases. Large-scale imports of basic foodstuffs, which have become an annual feature of the country's battle for survival, were needed in 1984 to meet the food shortages.

34.4.1.3 Mauritania

Most affected provinces: nine regions (out of a total of 12). The drought situation, which existed for over 10 years, became particularly serious in the course of 1983. In certain localities, rainfall levels were the lowest in 70 years. The Senegal River rose only to 10% of its normal rainy season level, thus preventing water recession agriculture, and the losses of animals and grazing land have been massive. Difficulties in the supply of milk and meat exist due to the large-scale sale of livestock at low prices. Cereal production was estimated at 15,000 tons (against 61,000 tons in 1981–1982), which represents only 6% of total consumption. Severe cases of malnutrition were recorded in some areas.

TABLE 34.2 The Most Deadly Natural Disasters of the Twentieth Century in Africa

Country	Year	Disaster	Region	Continent	Killed
Ethiopia	1972	Famine	E. Africa	Africa	600,000
Ethiopia	1984	Drought	E. Africa	Africa	300,000
Ethiopia	1974	Drought	E. Africa	Africa	200,000
Uganda	1901	Epidemic	E. Africa	Africa	200,000
Sudan	1984	Drought	N. Africa	Africa	150,000
Ethiopia	1973	Drought	E. Africa	Africa	100,000
Mozambique	1985	Drought	E. Africa	Africa	100,000
Niger	1923	Epidemic	W. Africa	Africa	100,000
NA	1972	Drought	W. Africa	Africa	62,500
NA	1973	Drought	W. Africa	Africa	62,500
NA	1974	Drought	W. Africa	Africa	62,500
NA	1943	Drought	E. Africa	Africa	35,000
Cape Verde Islands	1946	Drought	W. Africa	Africa	30,000
Niger	1931	Famine	W. Africa	Africa	26,000
Cape Verde Islands	1920	Drought	W. Africa	Africa	24,000
Niger	1910	Drought	W. Africa	Africa	21,250
Niger	1911	Drought	W. Africa	Africa	21,250
Niger	1912	Drought	W. Africa	Africa	21,250
Niger	1913	Drought	W. Africa	Africa	21,250
Somalia	1974	Drought	E. Africa	Africa	19,000
Morocco	1960	Earthquake	N. Africa	Africa	12,000
Cape Verde Islands	1900	Drought	W. Africa	Africa	11,000
Nigeria	1991	Epidemic	W. Africa	Africa	10,391

Source: EM-DAT, The OFDA/CRED International Disaster Database, www.md.ucl.ac.be/cred, accessed on July 22, 2016.

34.4.1.4 Zimbabwe

Most affected regions: all eight provinces (the outskirts of the country more than the center). According to official estimates, malnourished children total 464,200 and only 244,400 were assisted. Zimbabwe has suffered 3 years of drought, which was the worst in living memory. No surplus food was available and the situation was not improved with the following harvest. The maize shortfall over the following 15 months, entirely due to the drought, was estimated at 838,000 tons. Among the vulnerable groups, the health condition was often very serious. Drought relief programs were coordinated by the Zimbabwe government and included the distribution of basic food rations and supplementary feeding programs.

34.4.1.5 Ethiopia

Most affected regions: Wello, Gondar, Eritrea, and Tigre. Number of affected persons: 5,200,000 out of a total population of 32,395,000. The percentage of those under the age of 15 affected varies from 37% to 68% in different regions. In addition, about 2.2 million displaced people needed assistance. Several administrative regions have not had rain for three consecutive crop seasons. The most affected regions were all in northern Ethiopia. Serious food shortages also occurred in other administrative regions of Ethiopia. Some 52,950 people in the region of Bale, 278,830 in the region of Hararghe, and 35,250 in the region of Gojjam required immediate assistance; 122,000 in the Soha region, 2,530 in Arussi, and 79,880 in Gemu-Goffa were likely to require assistance. Moreover, 165,040 nomads in the Sidamo administrative region were also in dire need of assistance. In addition, some 221,610 displaced persons in the Gondar, Hararghe, Bale, and Sidamo regions required immediate assistance.

34.4.1.6 Mozambique

Most affected regions: Gaza, Inhambane, Maputo, Tete, Zambezia, Sofala, and Manica. Number of affected persons: 4,700,000. Mozambique has been experiencing severe drought for 4 years, with an aggravation of the situation in 1982 and 1983. Gaza, Inhambane, and Maputo were considered to be the most seriously affected. The FAO estimated that 4.7 million people, especially in rural areas, were affected, including 1.8 million in the southern provinces alone. Moreover, the Maputo province was struck by a cyclone at the end of January 1984 and more than half of the population was affected by the complete loss of summer crops.

34.4.2 Drought in Europe

Drought research and operational applications have been lagging behind the development in flood-prone areas. The European Drought Centre (EDC) interacts with the scientific and operational communities, as well as policy-makers and society, to raise the awareness of the drought hazard. The EDC is a virtual knowledge center, with the aim to coordinate drought-related activities in Europe, to better mitigate the environmental, social, and economic impacts of droughts. The EDC promotes collaboration and capacity building between scientists and the user community and thereby increases preparedness and resilience of society to drought. With the summers of 2003 and 2004 fresh in mind, when dry weather fueled raging forest fires, devastating crop failures, and widespread water rationing in Southern Europe, governments have begun to take action. Indicatively, Figure 34.4 shows the extent and severity of the 2003 drought in Europe based on the Standardized Precipitation Index (SPI).

Britain's Environment Agency warns that a winter with low rainfall in southern England could cause a serious drought, widespread environmental damage, and restrictions on water use. About 3.4 million residents in Kent and Sussex are already subject to restrictions on their water use, with 2.7 million of them being banned from using hosepipes. The Agency has warned that if the amount of rain does not increase, it is likely that more restrictions will be introduced. Similarly, the Royal Dutch Meteorological Institute (KNMI) also reported a dry winter in year 2005, with an average precipitation of 120 mm, just 60% of the historical average of 194 mm. January was especially dry, with just 17 mm, 25% of the normal of 69 mm. The lack of precipitation has caused the levels of rivers to be far below the normal. Moreover, the Danish Meteorological Institute (DMI) has registered a particularly dry January for Denmark; precipitation has been 57% of the normal. In fact, every

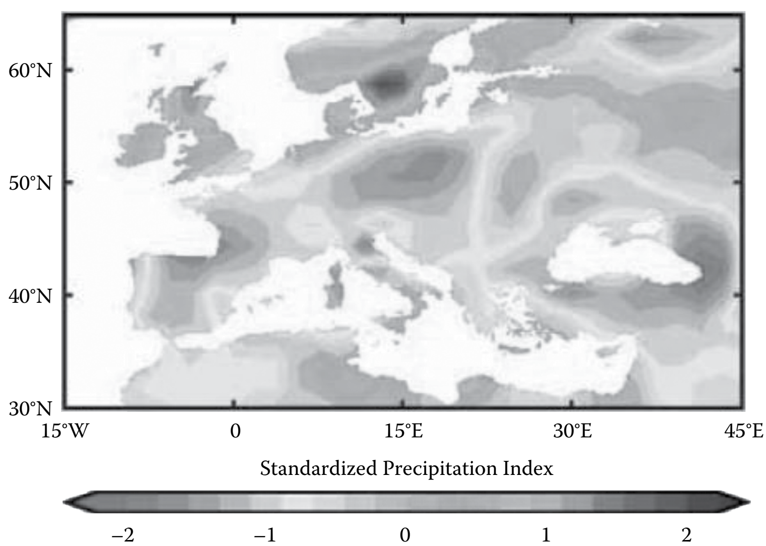


FIGURE 34.4 Extent and severity of the 2003 drought in Europe. (From www.euraqua.net, accessed on July 22, 2016.)

month since August 2005 has been dryer than normal. DMI reports that droughts are most pronounced in the northeast, with shallow lakes drying out and stressed vegetation. In addition, the French government has launched a campaign appealing to the public to use water sparingly and to the farmers to switch out of water-demanding crops such as maize, as France's water table has become seriously low after three very dry years in a row. The country will possibly face record water shortages this year, according to France's environment ministry. In Spain, which is said to be suffering its most serious drought in more than a century, the authorities have announced an emergency plan for the worst affected regions in the south and center of the country. The year 2005 was the driest year for the past 60 years in Spain, as the Spanish Meteorological Institute has declared. According to the Institute, the areas worst hit by drought are Extremadura, southeast Galicia, east Andalucia, Madrid, Castilla la Mancha, and parts of Aragon and Catalonia. Portugal is suffering in the same manner. According to the National Water Institute of Portugal, 80% of the country is currently experiencing its worst drought in 60 years. Losses to agriculture and livestock have been devastating.

Apart from the threat that drought poses to farmers, the water shortage, water quality problems, and more frequent and intense heat waves in Southern Europe could cause notable reductions in summer tourism, causing further economic losses. Temperature rise is likely to increase energy demand for air conditioning in summers, particularly in Southern Europe. Such extra power demand, compounded by a reduction in hydro-production and problems with cooling water availability, could cause disruption to energy supplies. Unfortunately, an increased frequency of severe droughts in Southern and Western Europe in the years to come seems to be most likely, according to several European and American climate studies. While a warmer and wetter climate is predicted in Northern Europe, particularly in Scandinavia, a dryer climate is forecast all year round in Southern Europe. Heat waves will be more numerous, dry periods will be longer, and there will be more intense precipitation events. Temperature rise and changing precipitation patterns are expected to exacerbate the already acute water shortage problem in southern and southeastern regions. Changes in the frequency and intensity of droughts and floods are projected, which could cause significant environmental, financial, and human losses throughout Europe.

34.4.3 Drought in America

The North America Drought Monitor (NA-DM) is a cooperative effort between drought experts in Canada, Mexico, and the United States to monitor drought across the continent on an ongoing basis. The program was initiated at a 3-day workshop in late April 2002 and is part of a larger effort to improve the monitoring of climate extremes on the continent. The NA-DM [51] is based on the highly successful U.S. Drought Monitor (USDM), and as such, is being developed to provide an ongoing comprehensive and integrated assessment of drought throughout all three countries. Since its inception in 1999, the USDM [80] has been operational in assessing and communicating the state of drought in the United States on a weekly basis. As with the USDM, the NA-DM blends science and art. There is no one "correct" way to measure drought. Drought indices are used to detect and measure droughts, but different indices measure drought in different ways, and no single index works under all circumstances [41]. Thus, the USDM concept was developed as a process that synthesizes multiple indices, outlooks, and local impacts into a single product for an assessment that best represents current drought conditions. Figure 34.5 presents a map showing drought conditions in North America on November 30, 2006.

Drought monitoring has become an integral part of drought planning, preparedness, and mitigation efforts at the national, regional, and local levels. Drought can develop in all regions of the continent, and its effects can be devastating. Since 1980, major droughts and heat waves within the United States alone have resulted in costs exceeding $100 billion, easily becoming one of the most costly weather-related disasters on the continent during that time [52]. But in today's global economy, the costs and effects of drought often extend beyond international borders. In 2002, the continuing drought in much of the southwestern United States and a prolonged period of drier-than-normal conditions in Mexico led to debates about shared water rights between the two countries. Similarly, in the north, the multiyear drought in

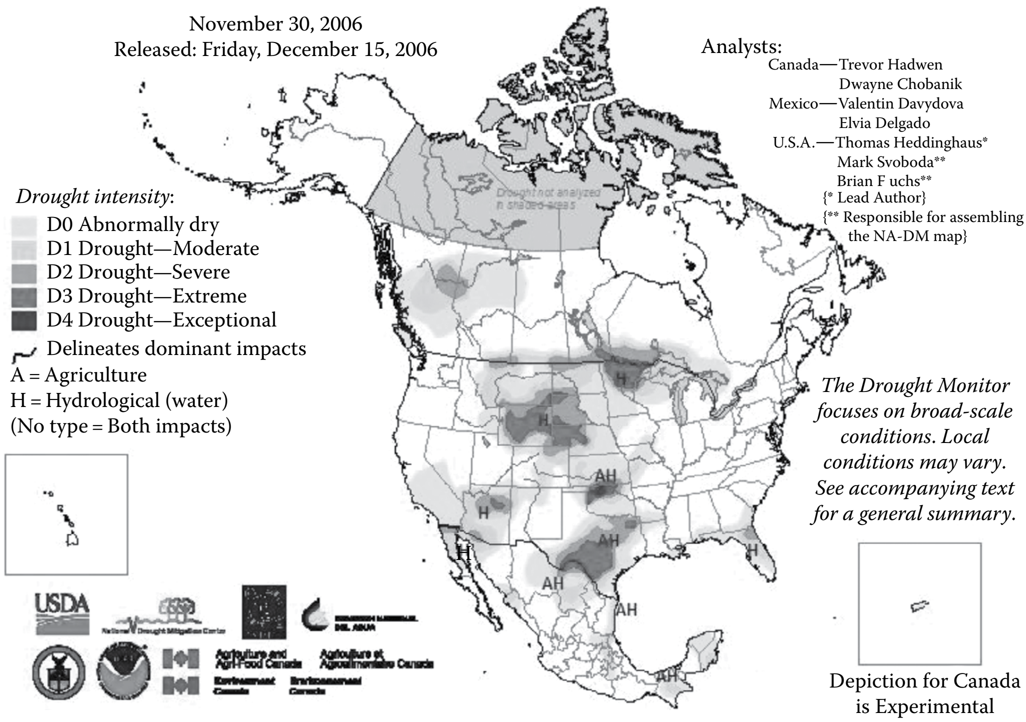


FIGURE 34.5 Drought conditions in North America on November 30, 2006. (From http://www.ncdc.noaa.gov/nadm.html.)

the northern Rockies and western Great Plains extended well into the agricultural prairies of Canada, greatly affecting agricultural productivity in the two countries, which account for much of the world's food production.

Although all three countries have active climate and drought monitoring programs, until recently, there has been only limited cooperation and coordination between the countries' drought experts. Past drought assessments typically have stopped at each country's borders, as differences in resources and policy objectives, as well as in differing methods for monitoring drought in each country, effectively prevented an integrated view of drought conditions across the continent. The NA-DM program is designed to overcome these past limitations with the objective of providing operational assessments of drought across the continent since 2003, where the monthly operational DM maps have become available to the general public. Major U.S. participants in the NA-DM program include National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center, NOAA's Climate Prediction Center, the U.S. Department of Agriculture, and the National Drought Mitigation Center. Major participants in Canada and Mexico include Agriculture and Agri-food Canada, the Meteorological Service of Canada, and the National Meteorological Service of Mexico (SMN, Servicio Meteorológico Nacional).

After the "dust bowl" years of the 1930s—in which much of the Great Plains region of North America suffered extreme drought conditions for years with devastating economic consequences—overall climate conditions have grown wetter with each passing decade. Station rain gauge records around the world reveal that over the last century, annual precipitation has increased by about 2.4 mm per decade, on average, with much of the increase concentrated in North America [23]. But despite the general increase in rainfall, in almost any given year, there has been a region on the map that experienced drought. Precipitation patterns can vary widely on regional scales, from one season to the next, and from year to year. It is hard to predict accurately where and how much rain will fall next week. It is harder still to forecast next year's rainfall patterns. Consider that, from 1995

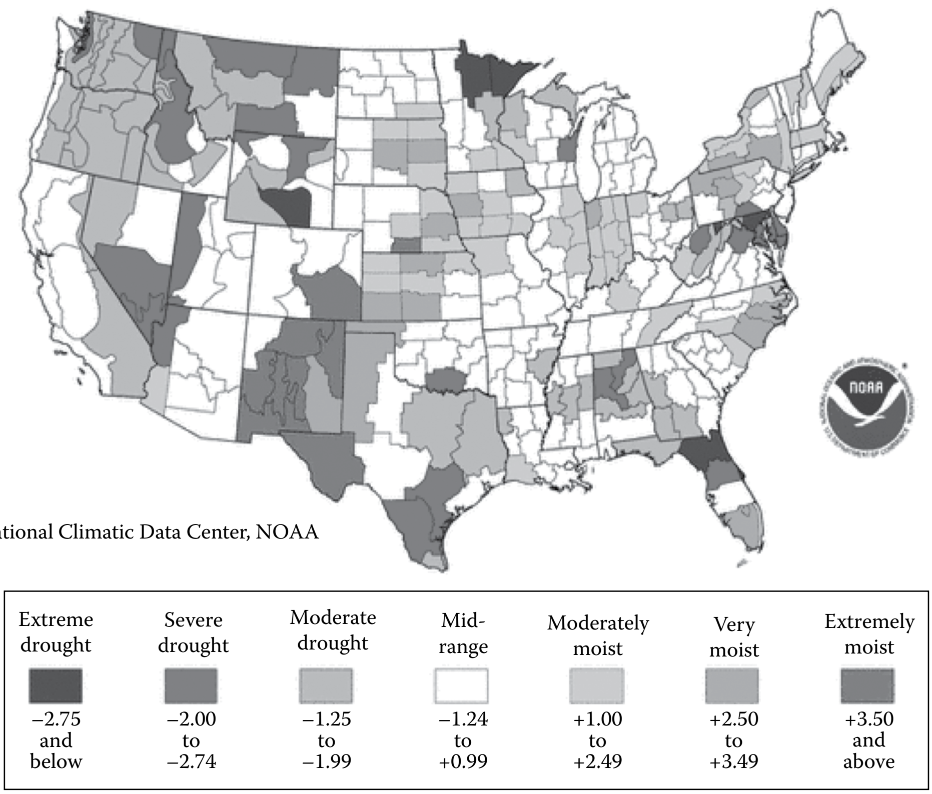
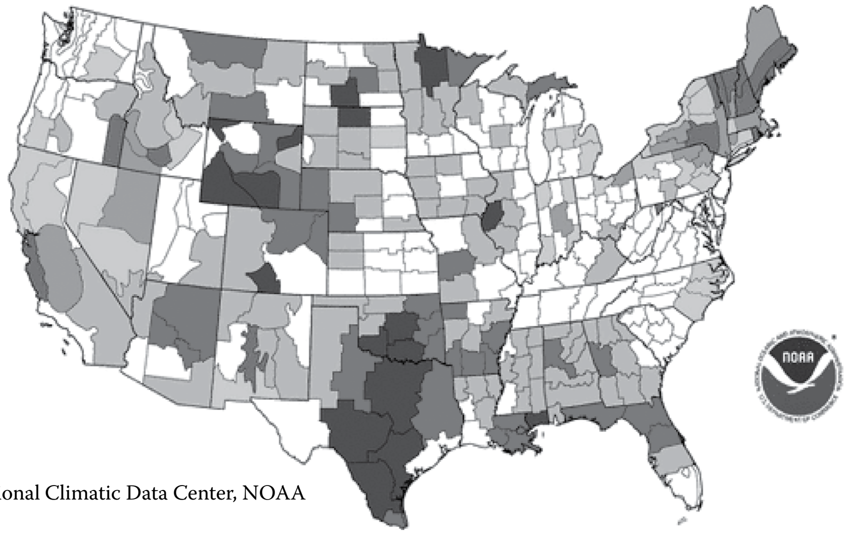


FIGURE 34.6 Short-term drought conditions assessed by Palmer Z Index, North America, August 2006.

to 1996, the northwestern and northeastern regions of the United States received higher-than-normal rainfall amounts, while precipitation in Alaska, eastern Canada, and the central and southwestern United States was substantially below normal [12]. Then, from January through the summer of 1998, there was excessive rainfall in California and across much of the central and southern United States, while the Gulf Coast states and Mexico experienced severe drought [13]. In the summer of 2000, drought hit hard in southeastern states such as Georgia and Alabama, while much of Texas has gone more than 67 consecutive days without rain. It seems that there is an increasing trend for more extreme "wet" and "dry" events, and for more often, as average global temperatures rise [24]. Figure 34.6 shows the short-term drought conditions assessed by the Palmer Z Index in North America for August 2006, and Figure 34.7 shows the corresponding long-term drought conditions for the same month.

34.4.4 Drought in Asia

A persistent multiyear drought in Central and Southwest Asia has affected close to 60 million people as of November 2001. Chronic political instability in many parts of this region and the military action in Afghanistan have further complicated the situation. The International Research Institute for Climate and Society (IRI) published a report about drought in Central and Southwest Asia that provides a climatic perspective on the severity and spatial extent of the ongoing drought and its social and economic impacts. The target audience for this report includes national, regional, and international policy-makers, humanitarian relief agencies, and members of the research community, as well as others with a general interest in Central and Southwest Asia and the causes and consequences of the persistent drought in the region. The report discusses underlying climatic mechanisms that might explain the causes for the persistent drought and presents seasonal climate forecasts and their implications for the region.



Extreme drought	Severe drought	Moderate drought	Mid-range	Moderately moist	Very moist	Extremely moist
−4.00 and below	−3.00 to −3.99	−2.00 to −2.99	−1.99 to +1.99	+2.00 to +2.99	+3.00 to +3.99	+4.00 and above

FIGURE 34.7 Long-term drought conditions assessed by Palmer Z Index, North America, August 2006.

The principal conclusions of this report are as follows: (1) Central and Southwest Asia represents the largest region of persistent drought over 3 years (1999–2001) anywhere in the world. (2) From a regional perspective, the drought of 2001 is the most severe in the past several decades. Significant shortfalls in precipitation have led to widespread social and economic impacts, particularly in Iran, Afghanistan, Western Pakistan, Tajikistan, Uzbekistan, and Turkmenistan. Agriculture, animal husbandry, water resources, and public health have been particularly stressed throughout the region. (3) Preliminary analysis suggests that the drought is related to large-scale variations in the climate across the Indian and Pacific Oceans, including the recent “La Niña” in the eastern Pacific. (4) Seasonal climate forecasting skill in Central and Southwest Asia is modest. IRI seasonal forecasts for the November 2001–April 2002 period have been consequently for climatology or equal likelihood of above-, near-, or below-normal precipitation in the region. While not indicative of any pronounced trends, a climatology forecast is less dire than the one indicating enhanced probabilities for below-normal precipitation.

34.4.4.1 Drought in Southeast Asia

The effects of the drought are clearly visible in Figure 34.8, where drought conditions in Southwest Asia according to NDVI values were generated from data collected by the Moderate Resolution Imaging Spectroradiometer (MODIS) on the National Aeronautics and Space Administration’s (NASA) Aqua and Terra satellites between February 18 and March 5, 2005. The image shows vegetation anomaly, a measure of plant density and health over a wide area. To determine the state of vegetation for 2005, the data are compared with the average of vegetation measurements collected during the same period in 2000–2004. Drier regions, where plants are less dense and healthy than normal, are brown, while areas with denser-than-average vegetation are green. In the latter half of February 2005, Southeast Asia was very dry, with plants showing clear signs of drought stress.

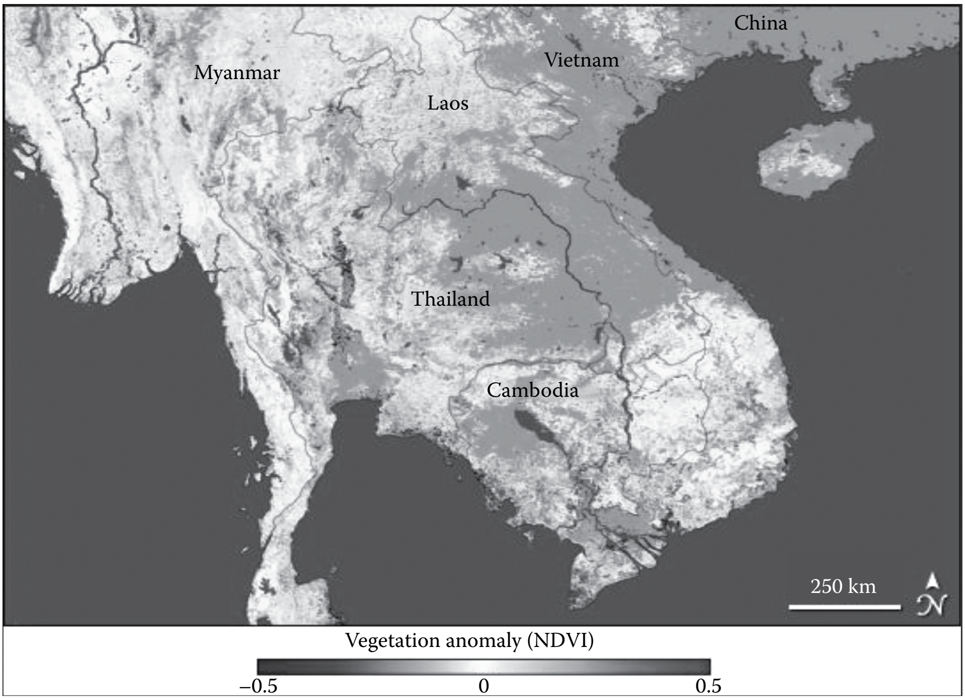


FIGURE 34.8 Drought conditions in Southwest Asia according to NDVI values. (From earthobservatory.nasa.gov/NaturalHazards.)

34.4.4.2 India

India is in South Asia. Drought is one of the oldest known disasters in India. The major drought-affected area of India is the Vidarbha region of the western Maharashtra state [36]. Drought mitigation is primarily due to the importance in regulating and controlling water resources. Water becomes a scarce resource. The lack of water due to environmental negligence empowers the upper class, who have de facto ownership and control of water resources. The local farmers, who cultivate other crops, and the local community have accepted the crisis as a reality. The government of Maharashtra has declared drought as a state issue, especially in the western region.

34.4.4.3 Pakistan

Pakistan has a long latitudinal extent from 24°N to 37°N and the rainfall variability during various seasons is considerably high and the country has a diversified climate. Therefore, this area consists mostly of arid and semiarid regions. There are two rainy seasons, namely, winter monsoon in December–March and summer monsoon in June–September. The rainfall difference in northern and southern Punjab and that in western, central, and coastal areas of Balochistan are also very significant [74]. The drought of 1998–2002 is considered the worst in 50 years in Pakistan. The drought began in 1997, developed as El Niño, increased its severity in 1998 and reached its peak in 2000 till 2001, and then gradually weakened in 2002. The extreme drought affected most of India and Afghanistan. The World Bank cautioned that the drought would inevitably hit the economic growth of Pakistan and delivered several hundred million dollars to help Pakistan through its worsening drought [63]. The drought was a result of 30% below normal monsoon rains in the country. Local farmers were heavily affected, since there was a significant impact on crop production. A lack of winter rains also increased the chances of moderate-to-extreme drought in Punjab and Khyber [63].

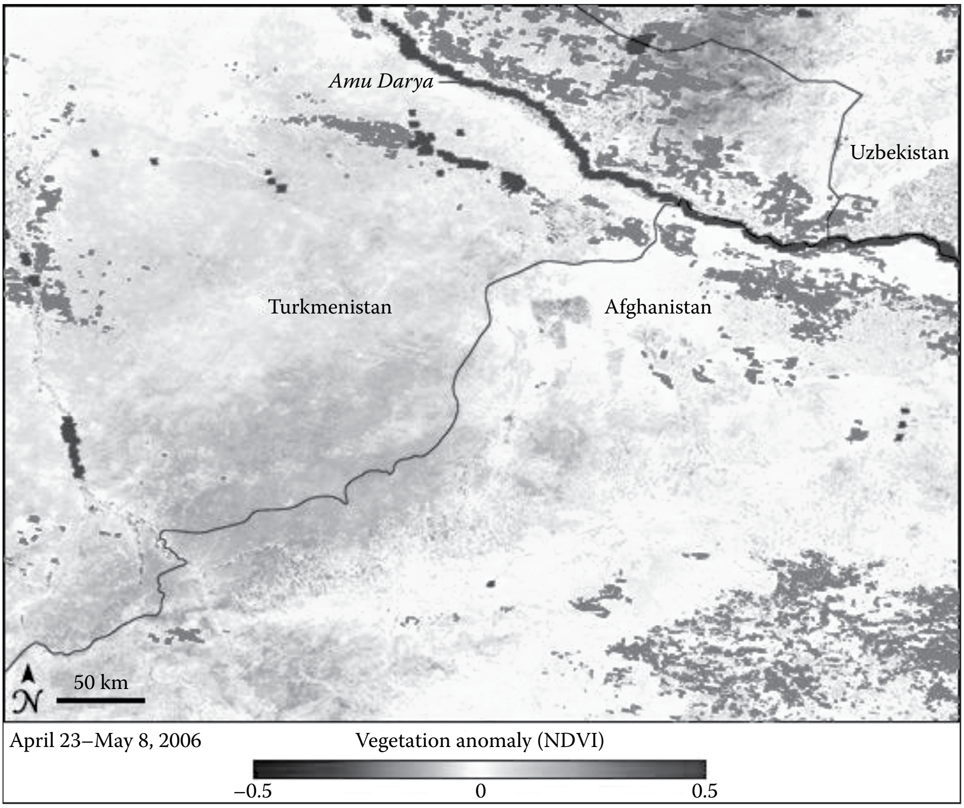


FIGURE 34.9 Drought conditions in Central Asia according to NDVI values. (From earthobservatory.nasa.gov/NaturalHazards.)

34.4.4.4 Drought in Central Asia

The effect of drought on vegetation in northern Afghanistan was evident in late April and early May 2006, when the data used to create Figure 34.9 were collected. The image, according to NDVI values, shows a *vegetation anomaly*—how well plants were growing, between April 23 and May 8, 2006, compared with their average growth for the same period during 2001 through 2005. The brown that dominates the image indicates that plants were less healthy than average, while brushes of green show where plants were growing better than average. In Afghanistan, the brown areas are in the north and west, where food shortages were reported. The green areas are located near the Amu Darya River, where farmers are probably less dependent on rainfall, because of access to irrigation water. Regions that were covered by clouds throughout the 16-day period are gray. The image was created from data collected by the MODIS on NASA's Terra satellite. Drought information on China and Iran are also provided.

34.4.4.5 China

China has two main climatic regions. The north and west are semiarid or arid with extreme temperature variation. The south and southeast are warmer and more humid, with year-round rainfall. The 1960–1962 drought contributed to a famine that killed millions during the Great Leap Forward. Beijing, located in northeast China, experienced a drought event between 1992 and 1993. Although a few months show above-normal precipitation, such as November 1992, with a rainfall amount of 43.3 mm, that is, 7.5 times the normal, there are negative departures from marked normal rainfall for the 1993 growing period. China's agricultural production was affected by drought in spring, summer, and fall. For much of the area of China, full precipitation during the period of drought was less than 100 mm, about 40%–50% less than normal. China has some regions that precipitation recorded even less than 50 mm, about 60%–90% below normal. With respect to temperature in this country, monthly average temperature departure was 2°C–3°C above normal and, in most of the cases, 2°C–4°C above normal. Indeed, high temperatures, coupled with sparse rainfall, quickened the act of spreading of drought. The National Climate Centre (NCC) developed the China Drought-Flood Climate Monitoring System in June 1995. The system is able to monitor the occurrence and extent of droughts and floods and analyze disasters comprehensively and forecast drought and flood.

34.4.4.6 Iran

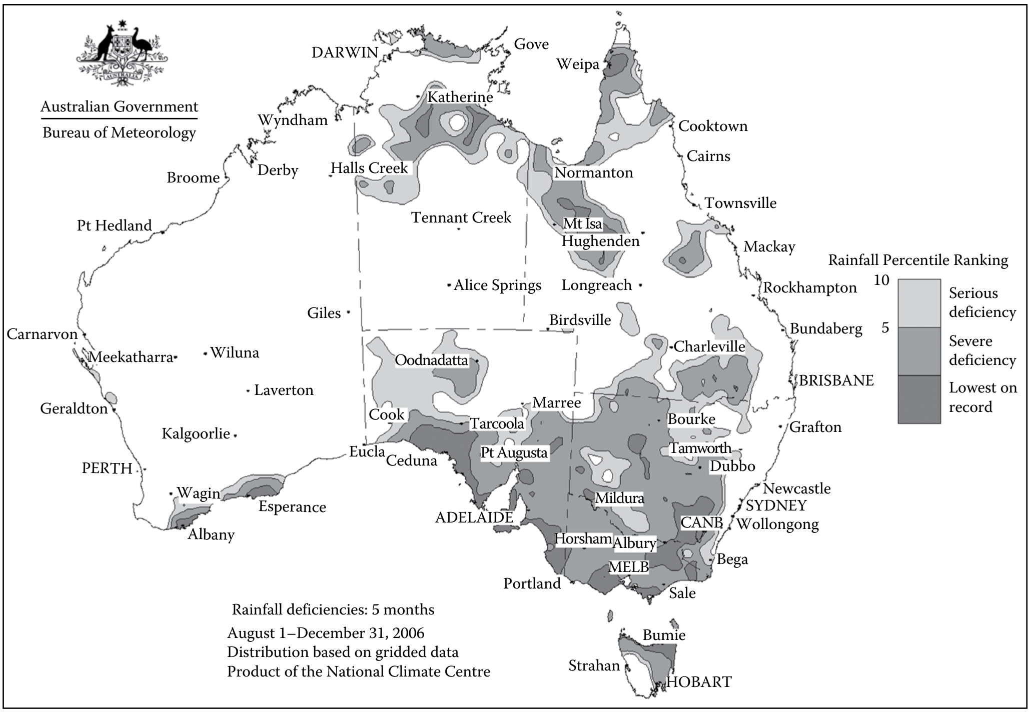
Iran is in Western Asia and also the second-largest country in the Middle East. The annual rainfall is 680 mm in the eastern part and more than 1700 mm in the western part. The eastern and central basins are arid, with less than 200 mm of precipitation. Average summer temperatures rarely exceed 38°C. The coastal plains of the Persian Gulf and Gulf of Oman in southern Iran have mild winters and very humid and hot summers. The annual precipitation in the south ranges from 135 to 355 mm [36]. Lake Urmia was the largest inland body of salt water in the Middle East and the second-largest hypersaline lake in the world, with an area varying from 5200 to 6000 km^2 in the twentieth century [40,109]. In recent years, the surface area of Lake Urmia has reduced. The average annual precipitation in the lake is about 341 mm and temperature is about 11.2°C. The lake has about 200 species of birds, including pelicans, egrets, ducks, and flamingos. There are 13 main rivers in Urmia and the two important rivers are Zarinneh Rud and Simineh Rud, which supply more than 50% of total surface water. Zayandeh Rud river basin is one of the most important watersheds in Iran, due to its high agricultural, industrial, and environmental potential, with an area of 26,917 km^2 in central Iran. In the recent decades, population growth and industrial advancement have made society more dependent on ever-decreasing water resources. In this area, a low irrigation efficiency leads to the consumption of 73% of the water supply for agriculture [107].

34.4.5 Drought in Oceania

For the 2006 calendar year, serious-to-severe rainfall deficiencies affected Australia, and specifically a large part of southeastern Queensland, much of the southern half of New South Wales, Victoria, northern and eastern Tasmania, southeastern South Australia, and a coastal strip in Western Australia. In addition, areas near Bourke and from Alice Springs to the south of Tarcoola also have deficiencies for this period. Indeed, the period from August to December 2006 was especially warm and dry, with severe rainfall deficiencies across the southern half of the country. A poor start to the northern wet season has also caused short-term rainfall deficiencies to develop across some parts of tropical Australia. In Figure 34.10, 34.5-month rainfall deficiencies in Australia for 2006 are presented. More specifically, in December 2006, rainfall totals were generally below average across the drought-affected parts of eastern and southern Australia, with widespread rainfall deficits over Tasmania, Victoria, South Australia, New South Wales, and southern Queensland. It was the driest year on record (back to 1900) across parts of the south.

34.4.5.1 Australia

The climate of Australia is significantly influenced by ocean currents, engaging the Indian Ocean Dipole and the El Niño–Southern Oscillation (ENSO), which is associated with periodic droughts in Australia [59]. Water deficits are frequent in many regions and cities of Australia in response to chronic shortages due to urbanization and drought episodes [74]. Australia is usually referred to as the land of extremes and has one of the most variable rainfall patterns in the world [15]. On average, a severe drought develops in some part of Australia once in 18 years [16]. The Commonwealth Scientific and Industrial Research Organization (CSIRO) has warned that Australia may experience up to 20% more drought months in the next 20 years [21]. Agriculture at the beginning of the twentieth century was considered the cornerstone of national wealth and accounted for 19.3% of Australia's GDP—the largest single sector with manufacturing



 Issued: 01/01/2007

FIGURE 34.10 Rainfall deficiency in Australia from August 1 to December 31, 2006. (From http://www.bom.gov.au.)

and mine trailing [7]. The twenty-first century estimated that across Australia, there are more than 2 million farm dams, with a total reserve capacity of about 8000 GL to combat drought [9]. The final reform to drought policy identifies the differences in local contexts and proposes a balance between providing financial assistance and promoting risk management.

34.4.5.2 New Zealand

The climate of New Zealand is temperate maritime with mean annual temperatures varying from 10°C in the south and up to 16°C in the north [57]. Droughts often occur in the eastern part of the country, where low rainfall for extended periods severely affects pastoral agriculture and agricultural production. A lack of surface and groundwater can be due to drought. Technology transfer programs have been developed and encourage the implementation of improved land farming techniques based on past drought experiences. The responsibility for drought risk management relies mainly on individuals, industry, organizations, agricultural managers, and local authorities, with the central government involvement only as a last resort [47].

34.5 Perspectives and Outlook

There is an increasing global awareness and concern about the risks in the environment and the persisting potential damage caused by hazards, including droughts. During the last decades, there have been continuous research efforts toward a more holistic approach to environmental hazards based on integrated methodologies, such as risk management framework. Several hazard mitigation and adaptation measures have been gradually considered and implemented, including land-use management, better planning for response and recovery, as well as emergency warnings.

Specifically, a global UN program was adopted with the objective to reduce the losses from natural hazards, including droughts, and the 1990s were declared as the International Decade for Natural Disaster Reduction (IDNDR) [78]. Indeed, the research challenge for environmental hazards has been to explore capabilities and skills and to adopt a broad perspective involving global change, among others, for a safer and sustainable environment for everybody at the present time, as well as in the future. Furthermore, the UN has adopted a program, namely, the international strategy for disaster reduction [92], involving several strategic goals, resulting in a number of priorities for action during the 2005–2015 period. Specifically, the program is based on the understanding of extreme events and disasters, the impacts of such events, and the strategies to manage the associated risks, which constitute a prerequisite for the development of adaptation strategies in the context of climate change and risk reduction within the disaster risk management framework [30,45].

Recently, the Sendai framework has been adopted as an international strategy for disaster reduction for the 2015–2030 period [91], which considers a better understanding of risk, involving all its dimensions, namely, vulnerability, exposure, and hazards. The main goal of this new program is to ensure that the disaster risk management involves all natural hazards and is developed at all levels, as well as within and across all sectors. The Sendai framework applies to the risk of frequent and infrequent, small-scale and large-scale, sudden and slow-onset disasters, such as droughts, caused by natural or man-made hazards, as well as related environmental, technological, and biological hazards and risks. The Sendai framework recognizes the significance of science and technology for disaster risk reduction. The overall objective of the program is to prevent new and reduce existing disaster risks through the implementation of integrated actions, which include technological, environmental, legal, educational, structural, economic, social, health, cultural, political, and institutional measures. Eventually, the aim remains to prevent and reduce hazard exposure and vulnerability to disaster, improve preparedness for response and recovery, and, as a result, strengthen resilience [91].

It is recognized that there is significant progress and development in all aspects of drought analysis. Specifically, drought quantification is implemented through indicators and indices, and the current scientific trend is the development of CDIs, leading to a single product, at different scales, using DSS toward regional or continental web drought platforms, which in certain cases are used operationally [80]. Indeed, during the last decade, a web services–based environment is being developed for the integration of regional and continental drought monitors and for the computation and display of spatially consistent multiple drought indicators on a global scale. Moreover, drought monitoring is considered semioperational; however, there are several operational applications internationally. In addition, the subject of drought risk assessment is also considered, involving, among others, risk estimation, vulnerability assessment, and damage assessment. Furthermore, drought management and governance emphasizes on drought impacts, drought preparedness and mitigation measures, as well as disaster prevention and relief policy.

At the present time, there is evidence for diachronically significant and steadily improving reliability of remote sensing data and methods, which is also related to computational and technological advancements. Similarly, the satellite systems are drastically increasing year by year, with new sensors and continuous improvement in spatial and temporal resolution. Moreover, there is a recent tendency to increase the number of available bands in these satellites resulting in new and valuable information. In addition, new types of remote sensing systems offer online open information for web-based platforms, which are also used for monitoring and detecting drought.

Special consideration should be given to the remote sensing potential in terms of data and methods in drought analysis and assessment. Specifically, for drought quantification, the remote sensing potential emphasizes on drought indices, which receive information from remote sensing sensors for mapping surface conditions, estimating parameters, and detecting drought features. Moreover, as already mentioned, the scientific trend in drought quantification involves the use of remotely sensed CDIs at different scales toward a global web-based drought platform. Similarly, drought monitoring has been considered based mainly on drought early warning systems (DEWS) using remotely sensed CDIs. Moreover, drought monitoring could also be addressed through remotely sensed vegetation dynamics at a local, regional, or global scale, since satellite-based vegetation indices have been extensively used in assessing agricultural drought, such as VHI and NDVI. Furthermore, remote sensing methods and data can be effectively employed in drought risk assessment, which include risk estimation, that is, drought event probabilities, magnitude–duration–frequency relationships, vulnerability assessment, mapping of drought areal extent, and damage assessment. Finally, the possible contribution of remote sensing to drought management policy could focus on relief, which involves assistance and/or intervention during or after drought. Other contributions could possibly involve drought preparedness, drought impacts, and mitigation measures, although remote sensing could also contribute to disaster prevention.

There are scientific challenges and future perspectives in drought analysis, whereas, at the same time, there are needs and requirements to be addressed. Specifically, the assessment of drought impacts requires the design of comprehensive databases based on users' needs. Moreover, drought preparedness and effective management requires access to relevant databases that allow forecasting, monitoring, and assessment. Similarly, it is necessary to assess drought forecasting skills, which means that a lack of good drought forecasting skills constitutes a constraint to improved mitigation, adaptation, and management. Moreover, drought monitor mapping based on CDIs has to be established in all drought-prone regions as a tool to better understand the drought severity. At the operational level, methodologies for drought monitor mapping should be developed with an emphasis on minimum, maximum, and optimum data layers. Needless to say, the integration of geographic information system (GIS), remote sensing, simulation models, and other computational methods has to be considered for more effective DEWS alerts. Specifically, there is an urgent need for a more risk-based proactive drought management framework, which would include a timely user-oriented DEWS. At the same time, there is a chance to provide design requirements for new satellite sensors, in particular, for drought mitigation. There is also a need for scheduling regular national and regional training workshops on drought monitor products [8,49,65,66,68,106].

34.6 Summary and Conclusions

This handbook provides a welcome addition to the literature on drought and water scarcity. This chapter addresses a different issue of water resources management during periods of drought and water scarcity. Indeed, water resources management remains a concern for many communities, which is amplified during periods of drought and water scarcity. If local and national authorities, as well as the international community, want to significantly reduce the impacts of drought, they must establish policies for drought risk management. The authorities should provide the framework for action and coordination that is flexible and responsive to the various situations in a drought condition. The learned lessons are very important. It is society's top priority to prevent the occurrence of disasters and to strengthen resilience.

This chapter, as the final chapter of a three-volume set, presents an overview of drought concepts, quantification, assessment, and management methodologies. Significant drought challenges have been presented, namely, natural and socioeconomic challenges. Moreover, historical case studies in the five continents have been briefly described. These challenges are directly related to technological and computational advancements. Specifically, the field of remote sensing in terms of data and methods, as well as new sensors and systems, may contribute significantly to the improvement of drought management strategies. The new trend is through the most current developments in theoretical and practical aspects of forecasting and monitoring droughts, assessing their consequences in many areas, and developing optimal management strategies to reduce or even prevent their negative effects on the environment, economy, and human life. Moreover, there are scientific challenges and future perspectives in drought analysis, whereas, at the same time, there are needs and requirements to be addressed.

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