Kurt Schwabe · José Albiac
Jeffery D. Connor · Rashid M. Hassan
Liliana Meza González *Editors*

Drought in Arid and Semi-Arid Regions

A Multi-Disciplinary and Cross-Country Perspective

Springer

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Foreword

Drought is often, for a variety of reasons, largely disregarded among the wide range of natural disasters that routinely affect societies in substantive ways. Because of its creeping or slow onset nature, its impacts accumulate over a long period of time; consequently, it is difficult to recognize both the onset and end of the event. In addition to being difficult to recognize, it also appears difficult to define as there is no universal definition of drought. Drought is best defined by region and impact sector. Literally, hundreds of definitions exist, often resulting in confusion as to whether or not a drought exists and its severity. This feature of drought sometimes leads to inaction on the part of government authorities, managers, and others. To complicate matters further, each drought episode also differs from all previous events in its intensity, duration, and spatial extent, and because of its long duration, droughts usually have multiple and migrating epicenters.

Impacts associated with drought are non-structural and, therefore, do not catch the imagination of the media and policy makers until those impacts reach devastating proportions, as we have seen in recent years in many countries throughout the world, including recent droughts in the Greater Horn of Africa, China, Southern Africa, and the United States. This is one reason why drought is referred to by many as an invisible natural hazard. Yet, drought affects more people globally than any other natural hazard and results in far-reaching and massive economic, social, and environmental impacts. Societal vulnerability to drought is constantly changing in response to increasing population, regional shifts of population, changes in land use, urbanization, applications of new technology, and many other factors. The projected increase in the frequency and severity of extreme climatic events, such as drought, will also exacerbate impacts. Because drought is a slow onset phenomenon with cumulative impacts, any increase in the duration of drought episodes will also affect the ability of society to recover since the time between events will be shortened.

The impacts of drought differ markedly between countries and even within countries because of the differing physical characteristics of drought and the societal context in which these events occur. People most closely associate the impacts of drought with the agricultural sector because of its direct effects on water availability and food production. Certainly, the agricultural sector remains one of the most vulnerable to an extended period of precipitation deficiency.

However, the impact of droughts today is more complex and often affects many other sectors. Most notable are impacts on transportation, energy production, tourism and recreation, ecosystem services, and health, as well as broader environmental and social impacts. Since the mid-1980s, the losses associated with drought in the United States have exceeded all other natural hazards, with the exception of hurricanes, whose primary impacts have occurred outside the agriculture sector.

The stated goal of this book, *Drought in Arid and Semi-Arid Environments*: *A Multi-Disciplinary and Cross-Country Perspective*, is to provide a synthesis of how scientists, water managers, and policy makers have managed drought and water scarcity, with particular reference to arid and semi-arid regions. The countries chosen for this comparative approach are Spain, Mexico, Australia, South Africa, and the United States. In my opinion, each of these countries present a clear opportunity to characterize the diverse array of approaches to drought management that illuminate the wide range of monitoring, early warning, impact assessment, mitigation, planning, and policy choices available to decision makers at all levels. The book provides a new and multidimensional assessment of drought and water scarcity and explores the many faces of drought in these diverse geographical settings. These case studies were initially captured at an International Drought Symposium held at the University of California, Riverside in 2010. Each of the chapters included in the book provides readers with a case study from which to extract valuable lessons that can be applied by many countries and adapted to their unique physical, social, institutional, and political settings. The book's editors are to be commended for their effort to assemble such a broad and rich perspective on such a timely and highly relevant topic.

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Preface

The goal of this book is to provide a synthesis of how scientists, water managers, and policy makers have considered drought and water scarcity in Spain, Mexico, Australia, South Africa, and the United States with attention to these countries arid and semiarid regions. A cross-country exposé for understanding the various elements of drought and drought management is a much more expedient approach to understanding the relative merits of various approaches to address drought and water scarcity than waiting for each country to explore such options over an extended and uncertain time horizon and drawing conclusions from those experiences. In addition to providing a cross-country description and comparison of drought awareness and experience, this book will also provide an assessment of drought from the perspective of multiple disciplines. To wit, efforts to efficiently mitigate and/or cope with the effects of drought requires an understanding of the biophysical aspects of drought, including the hydrologic and ecologic elements, as well as the technical, economic, and policy aspects. Hence, researchers from multiple disciplines within these countries, including disciplines such as agronomy, ecology, economics, hydrology, and irrigation technology, provided an assessment of drought experiences from their particular disciplinary perspective. Additionally, water manager and policy makers from each of these countries provided background and the current status of drought policy within their own country.

Each of the main sections in the book is discipline specific and provides the reader with an in-depth understanding of particular drought experiences, knowledge bases, and approaches to modeling drought from multiple countries. Together, these separate sections offer the reader with a better understanding of how to approach drought from a multidisciplinary perspective. The final chapter provides an in-depth comparison of drought experiences, descriptions, and approaches within each discipline by experts within each discipline. As such, after reading this book an interested reader should be able to identify both the successful and problematic approaches used to cope with various aspects of the droughts. Such an outcome should prove useful to researchers, practitioners, water managers, and policy makers who are looking to improve their baseline understanding of drought from different disciplines and levels of management. Furthermore, highlighting and identifying the different approaches and experiences from various integral disciplines across a multitude of countries should go a long way at improving our fundamental understanding of the interactions between physical impacts of drought and the effectiveness of mitigation policies on the economic consequences of droughts. Finally, a comparison of alternative policy outcomes and the evaluation of particular policy approaches from one country to another will enhance our understanding of how physical, institutional, and economic factors impact the effectiveness of one policy instrument relative to another.

The genesis of this book was developed on the heels of a symposium titled, "International Drought Symposium: Integrating Science and Policy" that took place on March 24–26, 2010 in Riverside, California (http://cnas.ucr.edu/drought-symposium/). The symposium, which was organized by the Water Science and Policy Center at the University of California, Riverside, brought together senior disciplinary experts from Spain, Australia, South Africa, Mexico, and California—all drought-prone areas—to sit together and share scientific and policy aspects related to drought and its mitigation in each of these areas. Most, but not all, of the initial drafts of these chapters were submitted to, and presented at, this symposium.

While there are many people and organizations that provided support in one way or another for this book and for which we are thankful, we want to begin by thanking Springer Press, and in particular the editors we interacted with directly—Fritz Schmuhl and Takeesha Moerland-Torpey—for their support and patience. We are especially grateful to Dr. Ariel Dinar, Professor and Director of the Water Science and Policy Center at the University of California, Riverside for bringing this group of scholars, water managers, and policy makers together and providing the platform and encouragement for this book. Without Ariel's support, this book would have never materialized. We have benefited greatly from numerous reviewers who provided critical and constructive comments during the review process in which all of the chapters were sent out to independent scholars. Special thanks go to these scholars, including Ken Baerenklau, Khaled Bali, Richard Clark, David Cresswell, Randy Dahlgren, Edwin Fagin, Theodor Geisel, Steve Grattan, Jonathon D. Kaplan, Nelson Lourenco, Siwa Msangi, Alfredo Ollero, Manuel Omedas, Andres Sahuquillo, Donald Suarez, Frank Ward, John Ward, and Santhi Wicks. Additionally, we are thankful to Marti Childs (EditPros LLC) for her extremely adept copy editing skills that allowed her to take chapters from five different countries and umpteen different formats and make sense of them all. The completion of this book was greatly facilitated by input and editing from Carol O'Brien, administrative assistant at the Water Science and Policy Center, University of California, Riverside.

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Jeffery D. Connor is a Senior Research Scientist in environmental economics with the CSIRO Ecosystem Sciences research group where he has previously held several research group management positions. Jeffery received Master's and Ph.D. degrees in Environmental and Resource Economics from Oregon State University. His research interests are in the areas of integrated biophysical—economics modeling for basin and catchment scale water policy analysis; the economics of water allocation, water quality, and salinity; the economics of land use change, the economics of land-based carbon sequestration; and evaluation and design of market-based policy for natural resource management. He has extensive experience advising international, Australian Commonwealth, state, and local water management agencies on water resource policy and economics. Jeffery is the author of more than 30 peer reviewed journal articles and book chapters.

Rashid Hassan is Professor and Director of the Centre for Environmental Economics and Policy in Africa (CEEPA), Faculty of Natural and Agricultural Sciences, University of Pretoria. He has wide international experience through his past and present involvement in international research organizations such as CIMMYT, Rockefeller Foundation, CGIAR Climate Change Challenge Program (CCCP), External Academic Advisory Panel for the World Development Report 2009 on Climate Change, World Bank, Steering Committee of the African Centre for Climate and Earth Stewardship Science-ACCESS, Stockholm Resilience Centre Board of Directors, GEF Science and Technical Advisory Panel-STAP IV, Science Panel of the Millennium Ecosystem Assessment; Member of the Science Council for the Consultative Group on International Agricultural Research

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Liliana Meza-González is a Research Fellow at the Program of Migration Issues at the Universidad Iberoamericana in Mexico City. She graduated with honors with a B.S. and an M.Sc. in Economics from the Instituto Tecnológico Autónomo de México (ITAM). She received an M.A and Ph.D. in Labor Economics from the University of Houston. Dr. Meza has published over 20 articles in specialized journals and has authored two books and coauthored five more on the subject of migration and labor economics. She has been invited as a speaker to several academic events in Mexico and other Latin American countries, as well as in the U.S. and Europe. She has been an invited scholar at American University and at Georgetown University, and has been a consultant to the World Bank and the Interamerican Development Bank. In 2005, she was appointed as Coordinator of the Program of Migration Issues at the Universidad Iberoamericana, and in 2007 was invited to collaborate with President Felipe Calderón as Technical Secretary of the Social Cabinet.

Kurt A. Schwabe serves as Associate Professor of Environmental Economics and Policy and Associate Director of the Water Science and Policy Center at the University of California, Riverside. His research specialization includes water economics, alternative policy instruments for pollution control, salinity and drainage management and policy, wildlife and fisheries management, and valuing ecosystem and forest services. His honors and awards include: the Flagship Fellowship (Australia's Commonwealth Scientific and Industrial Research Organization) to help address the salinity and drainage issues related to Australia's irrigated agricultural production; the Outstanding Journal Article Award of 2002 (*Journal of Agricultural and Resource Economics*); Editor's Citation for Excellence in Manuscript Review 2002 (*Journal of Environmental Quality*); Best Teaching Practices Award Recipient (Center for Teaching Excellence, Ohio University, 1998); and the Kenneth R. Keller Research Award for Excellence in Doctoral Research (North Carolina State University, 1996). He received a B.A. in Mathematics/Economics from Macalester College, M.S. in Economics from Duke University, and a Ph.D. in Economics from North Carolina State University.

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Chapter 1
Introduction

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Abstract Semi-arid and arid regions worldwide regularly confront drought. Some of the potentially significant and far reaching consequences of drought include impacts on: poverty rates, health, ecosystem services, land sustainability, and economic development. Unfortunately, recent climate change models predict that over the next 40 years, semi-arid and arid regions worldwide will experience an increase in the severity and intensity of drought as these regions encounter more aridity and less precipitation. The objective of this chapter is to introduce the issues that drought present in semi-arid and arid environments. We summarize our understanding of drought and its significant costs, as well as experience from managing and/or responding to drought from scientists, water managers, and policy makers across five countries—Australia, the United States, Mexico, South Africa, and Spain. The chapter provides a synopsis of arguments detailed in later

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chapters that explain how better understanding of drought indicators and experiences in management can reduce the cost of mitigation and adaptation.

1.1 Drought

Most populated regions, especially in arid and semi-arid environments, are experiencing substantial conflicts over freshwater resources as governments try to meet agricultural and urban water demands and leave flows for the environment (UNEP 1999). And while the global supply of freshwater resources has been nearly constant for the last 2,000 years (Hinrichsen et al. 1998), recent predictions from climate change models suggest less precipitation and hence further reductions in freshwater supplies in many of the already water-stressed semi-arid and arid regions worldwide, including parts of the Europe, Africa, Australia, and western United States (Shindell et al. 2006; Seager et al. 2007). These losses in freshwater supplies, coupled with increases in demand due to increased population growth that averages nearly one billion people per decade, portends unprecedented levels of water scarcity; consequently, how to allocate water among agricultural, urban, and environmental interests will be a challenging problem with global implications.

Historically, popular responses to water scarcity and drought have included conveying water from less-populated yet water-rich areas to more-populated yet water-poor regions, and storing water during non-drought periods in dams to be used during drought years. As Fig. 1.1 shows, the number of dams commissioned throughout the 20th century increased dramatically up until the 1980s. The

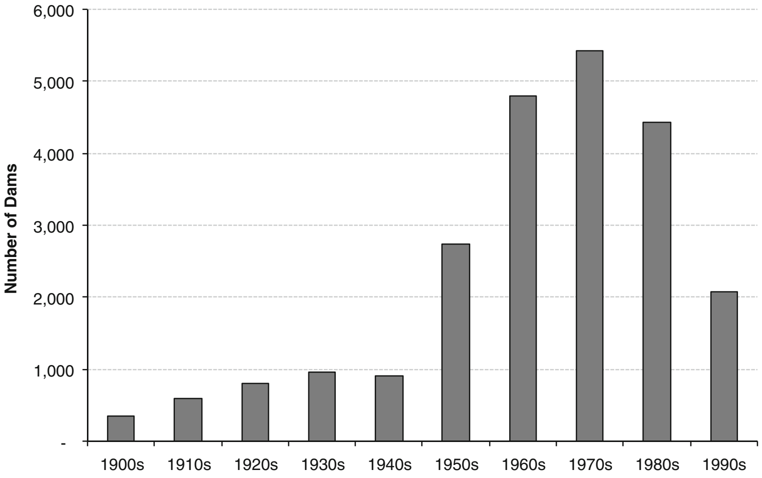

Fig. 1.1 Commissioning of large dams globally from 1900 to 2000. (adapted from Table 15, World's Water 2002–2003 data, Gleick 2011)

precipitous decrease in the number of new dams commissioned since the 1980s, though, is likely due to a number of factors, including, possibly, a public that is both more aware of the impacts of dams on the environment and better at communicating such awareness to its public officials, and fewer opportunities for low-cost river diversions to develop such storage. Another response has been to utilize available groundwater. This often unregulated open-access resource has been exploited to the point where most large aquifers worldwide are confronting extraction rates in excess of their recharge rates. For example, the Ogallala Aquifer in the central US, an aquifer that supports 1/5th of the irrigated acreage in the US, has an average area-weighted recharge rate of approximately 22 mm/year while the drawdown due to pumping for urban and agricultural uses is approximately 55 mm/year (McGuire 2007).

Reliance on large-scale engineering solutions or groundwater extraction, then, would seem to provide at best a partial fix to mitigating and coping with future drought events, especially if freshwater consumption rates continue to outpace population at growth rates similar to those experienced in the 1990s.[1] While there have been significant gains in water use efficiency from the largest demander of water supplies, irrigated agriculture, further gain in this direction is at best a partial fix given that overall consumption continues to rise and outpace supplies. Hence, continued water scarcity, and in particular drought, continually linger as a potentially severe stressor on economic development, agricultural production, and ecological sustainability. Such stress is compounded in arid and semi-arid regions where precipitation is often trumped by evapotranspiration. Spain, Australia, South Africa, Mexico, and the United States, for example, all contain regions experiencing periodic drought stress, which is not surprising given their similar climatic and physical conditions. Unfortunately, current and future availability of surface and groundwater resources in these regions are threatened not only by water scarcity arising from excess demand, but also by pollution and salinization, which are partly a consequence of the excess demand. With the looming threat of climate change and its expected impacts on water supplies, the frequency and severity of water shortages in these regions will likely increase in the future; impacts will be pervasive across natural, economic, cultural, and political systems.

The goal of this book is to provide insight and examples of how scientists, water managers, and policy have considered drought and water scarcity in arid and semi-arid regions of Spain, Mexico, Australia, South Africa, and the United States. These five countries, which contain nearly one-quarter of the irrigated land outside of India, Pakistan, and China (CIA 2008), each deal with their own complicated water issues and recurring droughts using a variety of mechanisms. The effectiveness of each country's approach to drought is likely a function of the biophysical characteristics of the region, the characteristics of the urban, agricultural,

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[1] Global freshwater consumption rose more than six-fold in the 1990 s, twice the rate of population growth, resulting in 1/3rd of the world's population living in countries with moderate to high water stress (UNEP 1999).

and environmental demand for water, as well as the particular array of technical, economic, institutional, and policy-related measures adopted to address not only water scarcity, but also poverty, energy, and land use reform. Formalized cross-country descriptions and experiences with drought from a research, management, and policy perspective are limited, and there is little organized narrative of their successes, failures, and challenges. Our hope is that this cross-country comparison and formalized treatise may help these and other countries with arid and semi-arid regions more expediently identify a larger array of feasible options for addressing drought and their potential consequences. We also aim to highlight and characterize how natural system attributes influence the effectiveness of such options.

In addition to providing a cross-country description of drought experience, this book provides an assessment of drought from multiple disciplines. Researchers from multiple disciplines, including agronomy, ecology, economics, hydrology, and irrigation technology, provide assessments of drought experiences from their own disciplinary perspectives. Additionally, water manager and policy makers from each of the countries represented in the book describe the backdrop and the current status of drought policy within their country or a particular region in their country. The final chapter summarizes the disciplinary-specific lessons to be taken from each section. The book is organized in sections of chapters by disciplinary focus; together, these separate sections provide the reader with a better understanding of how to approach drought from a multidisciplinary perspective. The goal is to allow researchers, practitioners, water managers, and policy makers to identify successful and problematic coping mechanisms for addressing the multifaceted aspects of drought.

The remaining sections of this chapter provide a general summary of drought conditions associated with each of the five countries targeted in this book; country-specific summaries of the chapters also are provided. Table 1.1 lists chapter contributions by discipline and country. As shown, there are seven chapters from Australia, six chapters from the United States, three chapters each from Mexico and South Africa, and six chapters from Spain. Included in Table 1.1 is the particular geographic focus within each country for each chapter. For instance, for the chapters associated with the United States, the geographic focus is primarily California except for Chap. 10 by Jenerette, which addresses ecological issues spanning the southwestern USA. We emphasize that even if the research is focused on a particular geographic area, the lessons, approaches, and issues can be extended to other semi-arid and arid regions suffering drought.

1.2 Australia

Australia is a continent of climatic extremes: it is the driest of all continents excluding the Antarctic, though the north is tropical and experiences extreme floods. Inter annual variation in inflows to Australian rivers is much greater than on any other continent. Droughts in southern Australia are also extreme. South-eastern

Table 1.1 Chapter Contributions by Country and Discipline[a]

Country	Section I agronomy, irrigation technology, and water supply	Section II ecological impacts of drought	Section III hydrology and drought	Section IV economic considerations and drought	Section V water management and policy
Australia	3, 5	12	16	20	24, 26
Geographic focus	Adelaide, Australia; South Australian Riverland	Murray-Darling Basin	Murray-Darling Basin	Murray-Darling Basin	Murray Darling Basin; Australia
United States	2, 7	10	17	19	25
Geographic focus	California	Southwestern USA	California	California	Southern California
Mexico	–	11	15	–	22
Geographic focus	–	Chihuahuan Desert of Northeastern Mexico	San Luis Potosí Basin	–	Mexico
South Africa	8	–	14	21	–
Geographic focus	Free State and Northwest provinces	–	Steenkoppies Dolomitic Aquifer	South Africa	–
Spain	4, 6	9	13	18	23
Geographic focus	Ebro Basin; Valencia Region	Iberian Peninsula	Júcar River Basin	Ebro Basin, Júcar River Basin, Spain	Ebro Basin

[a] Geographic areas in italics indicate specific areas focused on in a chapter; a general focus on the country as a whole is indicated by country name

Australia, especially in Australia's largest river basin the Murray Darling Basin, can experience very protracted droughts (seven to ten or more years in duration). Three such extreme droughts have occurred in the past 120 years. The most recent of these droughts, now known as "the Millennium Drought" (1997–2009) included the three consecutive years of lowest in-flows in the recorded hydrologic history to the Murray Darling Basin. Extreme protracted droughts have historically and continue to challenge Australia to evolve new and innovative ways to manage water resources. There are seven Australian chapters in this volume; all share a unified theme: drought induces innovation in water resource management.

Chapter 16 (Kirby et al.) sets the hydrologic scene for the other Australian chapters by suggesting, based on empirical results, that the severity of this recent drought is not only a result of another period of low rainfall, which has been the driver of previous droughts (e.g., the Federation Drought from 1895 to 1902), but also the result of higher temperatures. These higher temperatures lead to more soil moisture evaporation than in past droughts, thereby exacerbating the reduced runoff impacts from lower rainfall. Kirby et al. also provide insight into the nature of future droughts that could occur in the Murray Darling Basin under climate change, including the possibility of more protracted and frequent droughts. The authors conclude that the severity of the Millennium drought was beyond previous expectations used in river operations and water allocation planning, but that such drought and even more severe drought should be explicitly considered in future water planning.

A theme from Chap. 16—that droughts beyond previous experience are likely in the future and should be planned for—resonates through many of the remaining Australian chapters. Chapter 24 (Dreverman) provides perspective on how the operational managers of the system realized at the peak of the recent drought that existing contingency plans to ensure water for the most critical human needs, based on historically experienced dry periods, were not adequate to deal with the level of drought beyond historical precedent that were experienced in 2006–2009. Dreverman describes ad hoc adaptation, in the short term, at the height of the drought and then describes the challenges in developing a longer term plan that adequately deals with possible future droughts similar to or even more severe than the recent Millennium Drought.

Kendall (Chap. 26) offers a big picture perspective on how major droughts have spurred significant water management policy reforms in Australia. Prior to the Federation Drought (1895–1902), management of the River was a disparate matter of individual States initiatives. The severe Federation drought lead to failures, especially in being able to ship commodities downstream on what was then one of the primary modes of transport for commodities such as wheat and sheep produced in the interior of the Murray Darling Basin. This resulted in the first major agreement between States on River management with provisions to develop and share water for storages and to regulate and operate the river to ensure uninterrupted shipping. The chapter then outlines how nearly a century later the Millennium Drought sparked further major policy reform including a 1994 cap on diversion, the National Water Initiative with incentive money for states to implement wide ranging water policy reforms such as full adjudication of volumetric and monitored water rights, and even more recently the Water Act (2007) giving the Commonwealth authority to set limits on diversion that reduce current taking of water for consumptive purposes such as irrigation in order to enhance environmental flows.

Chapter 5 (Hayman and McCarthy) outlines the ways that irrigation adapted to more severe than anticipated drought and the challenges ahead in further adjustment. A theme in this chapter is the progress toward and further need for development of irrigation management strategies that are resilient in a future with more severe droughts. The chapter focuses on the South Australian Riverland, a region that grows predominantly high value wine and horticultural crops with a historically very reliable water supply for irrigation. Hayman and McCarthy coin the phrase “irrigation drought” in reference to the fact that the recent drought was the first one in history that significantly disrupted irrigation water supply. Indeed, allocations from 2007 to 2009 were in the range of 20–40 % of historic “normal levels.” Previously steady irrigation supplies were secured even in the face of varying annual inflows by a system of large dams.

Hayman and McCarthy document greater than expected improvements in irrigation efficiency in response to drought including a doubling of wine yields per mega litre in some cases. The chapter ends with a caution that there may be limits to efficiency as an adaptation strategy for irrigation and that there are trade-offs between efficiency and resilience. This potential is illustrated for the case of wine crops grown with reduced canopy cover. While such production systems can produce high quality crops with significantly less water, in the extreme heat that accompanied the drought such an approach offered little protection against heat damage with some crops faring poorly. Conversely, less efficiently grown crops, with more canopy, proved more resilient.

Chapter 3 (Maier et al.) provides a civil engineering, water resource planning perspective on water supply provision for Adelaide, the largest city in Australia dependent on the River Murray for water supply. The authors outline the historic evolution of water supply infrastructure. They describe how new dams in the local catchment and pipelines from the Murray were built from the beginning of the 20th century through the 1960s each time that growing demand coincided with a dry period. They then describe how in more recent time the cap on withdrawals from the Murray, a lack of well suited local dam sites and increasing scrutiny of dam environmental impacts have led to increasingly energy intensive and expensive infrastructure (e.g., desalinization) as the main engineering options to secure future supply.

Maier et al. conclude with a focus on challenges of future water supply planning with growing demand, possibilities of protracted droughts, and increasing emphasis on energy and greenhouse gas intensive supply options. They demonstrate concepts of risk-based planning, including stochastic shortfall probability and magnitude assessment for decisions to mix multiple supply options to meet supply reliability and greenhouse gas objectives. They present a case study of how risk-based assessment can be used when mixing newer less rain fall dependent sources with more variable traditional rainfed supply sources. Their main conclusion is that increased use of risk-based assessment is both feasible and necessary in municipal industrial water supply drought planning as it provides a systematic understanding of the trade-off in costs, reliability and environmental externalities such as greenhouse gas emissions.

Connor and Kaczan (Chap. 20) outline how water policy reforms through the 1990s established secure, monitored and enforced volumetric water property rights in the Murray Darling Basin. Economists have long argued for such property rights as a prerequisite for flexible and low transaction cost water trading. Yet such clearly defined volumetric water property rights remain an unrealized aspiration in many parts of the world, including countries often seen internationally as advocates of market based resource allocation such as the United States. The Australian experience shows that active water markets can be expected to arise once an adequate property right regime is in place. The chapter reviews the experience with water trade during the recent Millennium Drought documenting how the water market reallocated large volumes of water from lower value irrigation uses such as pasture and grain production to higher value perennial horticulture and wine production. A number of studies assessing the economic benefits of water trading are reviewed with the conclusion that the value of irrigated agricultural production was enhanced as a result of water trade on the order of hundreds of millions of dollars a year during the peak years of the drought. The chapter concludes with a discussion of some remaining challenges in property rights definitions that can both encourage low transactions costs water re-allocation and avoid adverse third party impacts that can arise from water trade.

Overton and Doody (Chap. 12) describe how a trend of growing extractions and very low inflows experienced during the Millennium drought significantly degraded Murray Darling Basin ecosystems. Floodplain forest ecosystems that had survived for centuries, including previous protracted droughts, died off on a scale of hundreds of thousands of hectares. The authors explain the threshold impacts reached through the combined effects of increased extraction and reduced flows resulting in intervals between inundations longer than these unique and highly valued ecosystems could endure. The authors echo the theme in other Australian chapters that new planning paradigms for water resource management will be required to deal with future droughts. They make the point that changes in ecosystem characteristics have already occurred and that return to pre-development ecological conditions, often the benchmark in current environmental flow management thinking, is simply not possible. They conclude that it would be advisable that future environmental flow management strategies begin with a realistic sense of where active floodplains (those likely to receive inundation on frequent enough intervals to ensure ecological functioning) can be maintained in the presence of drought and to identify constraints on the amount of water that we are willing to re-allocate from extractive uses.

One unifying theme of the Australian chapters is that the recent, 12 year long, low inflow period that ran from 1997 to 2009 was beyond previous precedent. This, and the growth in extractions in the decades leading up this dry period, resulted in unexpectedly severe disruptions to consumptive water supply and environmental degradation. All of the Australian chapters discuss aspects of how this has created a need to re-calibrate thinking about drought in water resource planning. Many of the Australian contributions to this book draw attention to the need to plan for future droughts based on assumptions outside of the historical hydrologic experience and the benefit of using systematic risk based approaches. Overall, the Australian contributions to this volume give the impression of a country that recognizes drought as an integral feature of their natural environment which will continue to pose large challenges for environment, food production and municipal industrial water supply. The chapters also demonstrate an ongoing legacy of successfully adapting to drought that many other countries can learn from including a history of substantial policy reforms to limit extractions, to reallocate water to environmental uses, and to create well defined and tradable water property rights.

1.3 California and the Southwestern United States

The southwestern United States consisting of Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming continue to experience some the greatest population growth rates in the country.[2] This region also is the most arid within the US, with forecasts that overwhelmingly suggest increased aridity and more intense and frequent drought (Seager et al. 2007). Climate predictions suggest that the region will suffer an average decline in runoff of 15 % between 2021 and 2040 relative to average surface moisture between 1950 and 2000 due to warmer air and less rain (Seager et al. 2007). Consequently, the region is likely to experience greater water scarcity and an increased susceptibility to drought. Water scarcity challenges are likely to be particularly acute in California, a focus for all but one US chapter in this book, as a result of a large and fast growing population and water demand already well in excess of supply in the arid south of the State.

There are six chapters in this volume that focus on drought in the southwestern part of the United States from multiple disciplines, including chapters in the sections *Agronomy, Irrigation Technology, and Water Supply* (Ayres; Hutmacher), *Ecological Impacts of Drought* (Jenerette), *Hydrology and Drought* (Mirchi et al.), *Economic Considerations and Drought* (Medellin et al.), and *Water Management and Policy* (Rossi et al.).

Mirchi et al. (Chap. 17) underscore why a better understanding of drought is crucial. As the authors emphasize, extensive observations and research demonstrate that California's climate is changing, with consequent impacts on

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[2] While the average growth rate for the US in the mid 2000s was around 0.9%, the rates of these particular states place them in the top fifteen states in terms of growth rates (with rates at or above 1.1%; US Census Bureau 2011).

California's water resources. For instance, several components of California's hydrologic cycle are likely to be influenced by climate change in ways that lead to scarcer and more variable water supply including (1) reduced snow accumulation and changed melt patterns, (2) reduced precipitation, (3) changed seasonal runoff, (4) increased evapotranspiration, (5) reduced stream flow, and (6) increased stress on groundwater and receiving water bodies. The implications of climate change, as the authors stress, are that California's water management plans need to be revised and updated to better deal with a higher level of water scarcity. One strategy that the authors highlight to better deal with drought is infrastructure improvement, including an obvious need for more water storage and more conveyance to balance supply and demand between the northern and southern regions in California. In the event that the large price tags turn the public sour to the idea of large infrastructure projects, the authors identify potential water saving opportunities that are likely less costly and more flexible, including the conjunctive use of surface and groundwater resources, increased conservation and reuse, ecosystem rehabilitation, and water quality protection, any or all of which might help mitigate the impacts of climate change in California.

One way California and the arid and semi-arid southwest U.S. may respond to drought is to consider how agriculture may be able to get by with less water. The issue and practicality of one strategy to use less water—deficit irrigation—is taken up in detail in Chap. 7. Hutmacher focuses on identifying crop and water management issues that may arise when such a strategy is considered. One conclusion that emerges from Hutmacher's insight and experience is that for deficit irrigation to be a cost-effective response to water shortages, knowledge of the various growth stages of the plant and their relative sensitivities to reduced water applications must be known. Hutmacher discusses experiences with using deficit irrigation on both annual crops and perennial crops, yet emphasizes that there is sparse information on the effects of deficit irrigation on crop production and quality if practiced over many years. Understanding the impacts of deficit irrigation on crop productivity and quality is just one piece of the puzzle, though, as other issues are important, including (1) designing irrigation scheduling to match the temporal sensitivities of the plant while controlling for other factors, (2) considering the physical and chemical properties of soils and how they may respond to deficit irrigation over time, and (3) how to monitor all these factors so growers can make timely decisions based on the characteristics of the plant, soil, climate, and market conditions. Much of this real-time information currently is available to aid growers, i.e., there is easy access to CIMIS reference evapotranspiration (ET_0) and weather data as well as soil and plant-based water status evaluation tools. Yet USDA surveys typically indicate that less than 15 % of growers utilize these tools to make irrigation scheduling decisions (USDA 2003).

In addition to deficit irrigation, there are a number of other on-farm strategies growers may employ to respond to drought. As Ayres identifies in Chap. 2, irrigation efficiency improvements can save water, similar to deficit irrigation, yet the long run sustainability of such practices will depend on how the soil conditions evolve. For example, replacing furrow irrigation with drip irrigation may result in significantly less water use. If salts and other toxic trace elements accumulate in the soil (e.g., boron, selenium), though, then this is a short-run strategy without some significant leaching periodically. Alternatively, growers may change the types of crops they grow to meet changes in water availability, grow winter crops when precipitation rates are high, or engage in dryland farming. Ayres is careful to point out that while these strategies may all save water, they may also result in increased cost or lost revenue; hence, attempting to achieve on-farm water savings is unlikely to be free. Ayres identifies other on-farm strategies to address water shortages (e.g., blending of higher and lower quality water sources) and emphasizes that such strategies may have impacts on other management decisions (e.g., fertilization); acknowledging these complementarities across input usage must be recognized for a full accounting of the impacts.

Medellin-Azuara, Howitt, and Lund, in Chap. 19, highlight the role governments and institutions can play in helping to mitigate drought impacts. Governments and institutions can influence the supply of and demand for water directly or indirectly via a multitude of actions, including the development of intra- and interregional water transfers, flexible water storage operations, conjunctive groundwater use, water conservation and water augmentation through desalination or reuse. In effect, the government confronts a portfolio of options. Medellin-Azuara et al. develop economic-engineering models to illustrate how such a portfolio approach to water management will help California best equip itself to minimize the impacts of drought. The economic-engineering models they develop can "…provide policy insights and economically efficient opportunities to allocate, store, and convey water in space and time for alternative water management portfolios and institutional constraints" (Medellin-Azuara et al.). A critical element in this portfolio approach to water management is the use of water markets to allocate scarce water to its highest valued uses. In one sense, the analysis provided by Medellin et al. emphasizes the usefulness of economic-engineering models to help predict, or explain, the impacts of drought on agricultural productivity, employment, and costs. One central message from this chapter is that a portfolio approach to addressing drought is cost-effective; another is that allowing prices to work through the use of water markets encourages cost-saving innovation and practice that can dramatically reduce the impacts of drought.

The primary responses to drought identified in this chapter mostly include water reductions and/or reallocations (trade) within the agricultural sector, understandably so given approximately 8 out of every 10 gallons of water in California goes to agriculture. In Chap. 25, though, Rossi et al. provide a unique perspective of how water districts in urban sectors, particularly within Southern California, are responding to water scarcity and drought. One distinct message from Chap. 25 is that a safe, reliable water supply is an essential ingredient to sustainable and economically successful communities. Indeed, the drought of 2007–2009 led to discussions of possible development restrictions on particularly fast-growing cities and the loss of water support programs for some agricultural regions. Given the uncertainty surrounding the reliability of water deliveries from Northern California, which currently provides the bulk of the supplies to many of the districts in the south, Rossi et al. note that water agencies are considering measures that address supply and demand opportunities at both the household and regional levels, including wastewater recycling, desalinization, conjunctive use, more dams to capture runoff, and water conservation programs to increase water use efficiency. To curb demand, both nonprice and price instruments are part of the arsenal of tools available to agencies, although there is concern that non-price instruments may also reduce agency revenues. There also is concern with public opinion regarding different sorts of measures, particular those involving rate increases, to the extent that such measures face uncertainty regarding their passage. As Rossi et al. note, then, water management in urban environments involves not only identifying and developing cost-effective strategies to reduce the level of water scarcity, it also involves persuading the public to buy into the plans.

While the above-mentioned California chapters focus on how household and local, regional, and statewide agencies may address drought via behavioral, technological, or institutional change, Jenerette (Chap. 10) discusses the effects of drought on ecological systems and stresses the point that one may observe significant and widespread changes to biotic community composition and disparate transformations in ecosystem functioning; furthermore, these changes can persist indefinitely even after the drought conditions subside. Given such consequences, Jenerette suggests the need to evaluate ecosystem services in the context of their required water uses so that the effects of droughts can be better quantified and potentially mitigated. This area of study, termed *ecohydrology*, is a rapidly growing field that integrates ecosystem science with hydrologic science, and accentuates the coupling between hydrologic cycles and ecological functioning. Drought, through its impacts on nutrient deposition, species composition, landscape configuration, leads to unique and often unexpected ecological changes. In response to these unwelcome changes society can build in redundancy to minimize drought impacts on critical resources. Such responses, as Jenerette suggests, can be found in society's increased interest in protecting rare and endangered species which has led to large allocations of water in California reserved for endangered fish reproduction. As researchers come to better understand the dynamics of pulse events and, subsequently, better predict how whole ecosystems may respond to discontinuous and variable precipitation regimes, fewer resources will be required for mitigating drought.

There are several themes that can be pulled from these chapters that address California and the Southwest's experience with water scarcity and drought. First, there seem to be a number of opportunities available to mitigate the impacts of drought, ranging from farm-level responses, urban water management strategies, state-wide infrastructure adjustments, to institutional change. As such, no single strategy is a magic elixir to addressing drought; many lower cost solutions to addressing drought will be encouraged by institutional structures that are flexible and allow for a vast array of management responses. The fuller implementation of water markets, as Medellin et al. suggest, would be one type of institutional adjustment to allow such flexible responses. A second theme is that a portfolio approach to water management should be, and is being, adopted, whether it be at the farm-level, or regional or statewide level. Such strategies are least-cost approaches to addressing drought and serve to increase water supply reliability and/or lower the cost of adaptation and mitigation. A third theme is that a better understanding is needed of the possible impacts of drought on ecosystems and services that they either directly or indirectly provide society. Such knowledge could improve our ability to mitigate and cope with drought using fewer resources.

1.4 Mexico

Water in Mexico is scarce, and scarcity has become more severe in recent years. From 1996 to 2009 Mexico experienced rainfall deficits, provoking significant drought in different regions of the country. Water scarcity has transformed Mexico from a net maize exporter to net maize importer, and has subsequently lead to agricultural price increases and increases in prices of upstream and downstream products. Drought also has resulted in increased desertification and environmental damages. Given that almost one third of Mexico's population live in rural areas, and of this population most have no access to irrigation technology, drought has resulted in increased poverty.

Geographically, the northern border states in Mexico are generally the most affected by drought given the limited precipitation associated with this part of the country. According to the National Institute of Statistics and Geography, the average annual precipitation in Mexico is 777 mm. In the north part of the country, this figure reaches 250 mm, while in the southeast and the south Pacific coast the annual average precipitation is between 2,000 and 4,000 mm. Unfortunately, and as will be discussed in the chapters below, the degree of water scarcity is exacerbated by some government policies that encourage the inefficient usage of water (e.g., an energy subsidy which encourages excessive pumping). Consequently, drought episodes are worsened which give rise to social and political problems.

From a country-level perspective, average annual availability of water per capita in Mexico is approximately 4,288 m^3. This is significantly lower than the average 17,650 m^3 reported by the FAO across 174 countries (FAO 2010). Moreover, in just under 60 years per-capita availability of water in Mexico has fallen by 75 %. Mexico had 18,035 m^3 (635,650 cubic feet) of water per Mexican inhabitant per year in 1950, but an annual total of just 4,312 m^3 per inhabitant in 2007. Regarding extraction of water for public use, around 286 l of water were extracted per habitant per day in 2008, which is more than enough to fulfill daily requirements of water according to international daily standards of 150–170 l (WHO 2004). However, it is estimated that 44 % of the water in Mexico is lost in the distribution process, resulting in only 160 l being supplied. It is worth noting that even when the supply of water for public use seems sufficient, substantial regional variability occurs within the country such that 6 out of the 13 water administration regions do not have a sufficient supply of water to fulfill daily requirements when conveyance losses are acknowledged.

The papers in this book that discuss drought in Mexico suggest that water management in Mexico is far from ideal, and that this is deepening the problems associated to water scarcity in certain basins. The work by Meza, Sanginés and Pulidos in Chap. 22 establishes that water management and policy in Mexico has much room for improvement, including pricing policies that at a minimum cover water provision costs, indirect subsidies that encourage overuse, and no mechanism to move water to its higher-valued uses. To ensure water is adequately preserved and used, they propose a series of policy interventions and argue that these interventions must be arranged in an integral framework that includes not only authorities at the basin, municipality, and state levels, but also groups of users and a national authority with a holistic view of the country's water problems.

The authors explain that Mexico has 27 river basins, covering the entire national territory. Inside each basin, authorities are responsible for integrating all water uses in the region. Such responsibility includes identifying the interactions among superficial and groundwater sources, ensuring the provision of high-quality water for all users, identification of the relationships among water and other natural resources of the basin, and consideration of the optimal water use to promote economic and social development in the region. The existing basins are organized and administered by the National Water Commission through boards (councils) with federal, state, municipal, and major users′ representatives, including those representing the environment. This chapter shows that Mexico has advanced dramatically in the past few years in terms of water administration, but problems still remain. The authors propose that these problems have to be addressed in a more integral and coordinated way. For instance, further intervention is needed in water pricing as water is still highly subsidized in Mexico, albeit the National Water Law eliminated federal subsidies to this resource in 2004. Subsidies change incentives and promote overuse; moreover, price differences encourage inequalities.

Other areas where real efforts are required are related to infrastructure. Meza et al. suggest that despite recent significant water-related investments, the number of Mexicans lacking access to potable water and sewerage services is unacceptable. Additionally, the authors' argue that the low average productivity of Mexico's agricultural sector is partly explained by the lack of irrigation infrastructure, especially in regions where weather is not suitable for many high value crops without irrigation. They show that in Mexico, only 5.6 % of the agricultural land is equipped for irrigation, meaning that over 1 million km^2 of the territory dedicated to agriculture (94.4 %) depends on local precipitation. Irrigated agriculture contributes nearly 50 % of the total value of agricultural production and accounts for approximately 70 % of Mexico's agricultural exports. Decisions regarding where to invest in irrigation have to be made at the federal level so that national interests are prioritized yet with significant attention to basin-level costs and benefits.

In Chap. 11, Pisanty, Pérez and Galvez focus on how drought, and in particular man's contribution to water scarcity, has affected ecosystem health in particular areas of Mexico. They also identify some indicator species that portend significant losses unless water use and management strategies are adjusted. The authors argue that a unique system of wetlands in the different valleys of the Cuatrociénegas region, Coahuila, in the northeast of Mexico, have been under siege due to inefficient irrigation and conveyance systems, and the unregulated proliferation of groundwater wells. They identify both commercial fields and the ejidos (a system of common land ownership) as significant contributors to ecosystem degradation, which includes losses of recreational use of lakes, ponds and springs.

The authors model the consequences of current trends characterizing the remaining water bodies of the Churince System and find that further reductions in stream flow will result in a growing level of soil depressions that will be colonized by species that can take advantage of the humidity these riparian habitats offer and tolerate high salinity levels. Eventually, though, the process of sinkhole formation could decrease progressively if drying continues through time; vegetation in the sinkholes would eventually die, and a set of salty depressions would become the dominant landscape around the dry water bodies.

In Chap. 15 Carrillo and Ouysse analyze the physical and chemical characteristics of San Luis Potosí (SLP) drainage basin groundwater. They conclude that management to balance extractions with recharge requires an understanding of the spatial dimension over which these activities can occur based on systems flow theory. They highlight how water table levels and quality in one aquifer may depend not only on local basin additions and extractions, but also on additions and extractions from sources outside the basin, albeit over different time scales.

Carrillo and Ouysse outline several ways that a better understanding of regional spatial and temporal water balance may be helpful, including: (1) implementing policies intended to protect the vulnerable regional system to recharge changes (quality and quantity), (2) verifying if the regional flow is under extraction elsewhere beyond the SLP-Basin, (3) identifying the location of the recharge area of the SLP-Basin to propose some protective measures in the basin and along the flow path, (4) controlling the rate of extraction in time and space to minimize the loss of water quality, (5) controlling present extraction schemes so as to minimize subsidence effects and the possibility of artificial recharge with sewage effluents, and (6) developing programs of payment for hydrological environmental services in the recharge areas of the regional flow.

1.5 Spain

Most of the Iberian Peninsula is under a Mediterranean climate and experiences cyclical droughts. Extreme drought lasting several years is not uncommon, having occurred in the 1940s, 1980s, 1990s and 2000s. The impacts of these extreme cyclical droughts on human activities and the environment are significant, with average river flow for the country falling by 30 %; some river basins experience river flow reductions of 70 %. Over the past 50 years, the presence of drought and pressure for water resources to meet economic development has contributed to a two-fold increase in water extractions with commensurate increases in pollution loads. Nowhere is this more noticeable then in the river basins of southern and eastern Spain, where the demand for water for irrigation and economic development are intense. As water scarcity and degradation intensifies in these basins, economic and environmental costs rise. Indeed, the environmental effects are especially worrying because adjustment to scarcity and drought fall mainly on environmental flows, with escalating damages to aquatic ecosystems.

Because of these drought events, which have spanned centuries, Spain has developed a long tradition of water planning by basin authorities and allowed stakeholders early on to be actively involved in the design, implementation and enforcement processes. While in decades past, planning basically consisted of emergency management measures and piecemeal reactionary responses, more recently complex and sophisticated strategies have been developed for every basin authority since 2007. Several of the Spanish chapters in this book describe aspects of these complex and sophisticated strategies: especially Chaps. 13, 18 and 23.

Droughts in Spain are quite frequent and long lasting due to the level of basin water scarcity and hydrological variability as emphasized by Andreu, Ferrer-Polo, Angel Pérez, Solera, and Paredes-Arquiola in Chap. 13. Focusing on the Jucar basin, located in eastern Spain, Andreu et al. describe the three main planning and preparation processes associated with the management of drought response. First, there is integrated water planning that includes proactive measures to avoid operative failures in water systems. The second component entails the specific drought plan, with continuous monitoring of drought indicators to detect droughts. These indicators trigger the proactive and reactive measures designed to meet every stage of severity of drought situations. The third component is the activation of the basin drought committee to coordinate the implementation and enforcement of particular drought measures. The authors identify how each component was enacted during the 2004–2008 drought in the Jucar basin and highlight how drought management actions relied heavily on decision support systems.

In Chap. 18, Albiac, Esteban, Tapia, and Rivas analyze policy measures addressing water scarcity and drought in Spain, and focus on drought impacts and management responses across two basins, the Ebro and Jucar basins. Water scarcity and water quality degradation are shown to be due largely to the broad expansion of irrigated agriculture and the strong industrial and urban development that took place during the second half of the twentieth century. The authors describe some of the sophisticated physical and institutional arrangements for management of droughts and the achievements from approaches to date. The authors stress, however, that as river and stream flows dwindle and aquifer storage volumes fall, continued scarcity will exact a higher and higher toll, both from an economic and environmental perspective, absent further reforms and innovations.

A review of the actual operations management of water resources water basin authorities in Spain during drought events is provided by García-Vera and Galván-Plaza in Chap. 23. Examples are provided with particular attention to the Ebro basin. Reconsideration of water management practices is a regular process in Spain because of the large temporal variation of resources with frequent drought episodes. The chapter highlights and discusses the key requirements for good operational water management: suitable institutions, planning at basin level, updated and accurate information and knowledge on hydrological processes, co-responsibility by all stakeholders in decision making, and general public participation.

Chapter 4 and 6 focus on irrigation sector adapatation to drought. In Chap. 4, Playán et al. present a discussion of the responses of growers to drought in the Ebro basin. One response by growers, a response that has been implemented on one-fourth of the irrigated land in the basin, has been to invest in advanced irrigation technologies. Another response spearheaded by the water user associations in the basin has been to commission and implement software programs supporting water management operations in irrigation districts to improve conveyance efficiency. Chapter 4 analyzes the impact of both measures—investments in irrigation infrastructure and better management—on the hydrology and economic performance of irrigated agriculture. New solutions for further drought adaptation and crop profitability enhancement are presented. These solutions are based on automated irrigation scheduling and operation by combining remotely controlled networks, good management of the water user associations, meteorological databases, and innovative irrigation engineering tools.

García-Mollá, Sanchis-Ibor, Ortega-Reigand and Avellá-Reus, in Chap. 6, analyze grower response to drought in three irrigation areas of Valencia, a state in Eastern Spain. Adaptation and mitigation, they point out, have included curtailing irrigation on low-valued crops, investing in more irrigation infrastructure and higher efficiency irrigation systems, using more subsurface and non-conventional water sources, and installing more metering devices to better monitor and control extractions. In the Vinalopo basin, a basin heavily reliant on aquifer pumping, drought and increasing demand have resulted in unsustainable extraction with the water table levels dropping over 500 m. García-Mollá, et al. highlight that a portfolio of responses are being considered and implemented including importing water, reusing treated wastewater, building reservoirs, and investing in advanced irrigation technologies. In the case of the Vall d'Uixo irrigation district, which primarily relies on an aquifer that suffers from both over-extraction and a threat of saline intrusion, responses have included consolidation of existing water user associations coupled with irrigation efficiency improvements. Finally, in the lower Jucar irrigation area, the third area considered in Chap. 6, water extractions have fallen from 700 down to 200 million m^3 over the past 30 years due to drought-induced declining river flows. Responses identified in this case include crop switching, land abandonment, investments in higher efficiency irrigation technologies, and reuse of drainage flows. The authors stress, though, that the reuse of drainage flows have had negative impacts on important ecosystems fed by these return flows, an underappreciated consequence identified in other research (Qureshi et al. 2010).

In Chap. 9, Ibáñez and Caiola investigate the impacts of water scarcity and drought on ecosystems in Spain. Significant increases in water extractions in recent decades have added to the water stress present in most basins throughout Spain. Consequently, most rivers, lakes, estuaries and wetlands are being degraded by the reduction and regularization of flow regimes and the depletion of aquifers. Ibáñez and Caiola emphasize that the effects of this degradation to ecosystems include major changes in biotic communities, habitat loss, alteration of ecosystem metabolism, proliferation of eurytolerant and invasive species, and reduced resilience to global change. The authors suggest that implementing and enforcing measures for adequate environmental flow regimes in basins is a necessary measure to protect ecosystems from further degradation.

1.6 South Africa

Climatically, South Africa is a semi-arid country vulnerable to water stress, particularly drought. Recorded droughts have been experienced since the early 1800 s in both the winter and summer rainfall regions of South Africa and have inflicted major socioeconomic damages. South Africa experienced below average rainfall during all decades of the past millennium except the 1950s and 1970s, with worsening trends in frequency and duration of drought in recent times. There is evidence that inter-annual variability in precipitation is inherent and drought is a recurrent feature of the South African climate that is found to be highly correlated with El Niño years. The country has, however, developed sophisticated water management infrastructures that enhance its ability to cope with water stress situations, including drought episodes. Drought management strategies and policies in the country have also evolved in significant ways over the past few decades. Indeed, the South Africa's water sector undertook radical policy reforms after 1994 that have important implications for drought management.

Despite all these efforts, drought continues to inflict significant damages on the South Africa economy and its people, particularly the more vulnerable poor. The impacts of drought on South Africa are widespread, and include losses in agricultural productivity, farm incomes and food security via reductions in crop yield, and losses in livestock productivity through reductions in grazing quality. Additional impacts include: reductions in power generation capacity through less stream flow, increases in forest and range fires due to less moisture, stresses on vegetation, wildlife and ecosystems, forced migration, less reliable water, and other drought-related health that issues impact general household welfare.

Three chapters in this book address drought management in South Africa. Chapter 8 (Durand) presents an example of the agricultural impacts of drought on crop yields using the case of maize, the main food staple and a major grain crop produced in South Africa. The chapter focuses on maize production and the differing impacts on commercial and subsistence maize farmers. Determinants of vulnerability of these two maize production systems under rainfed and irrigation conditions and their responses are reviewed. The chapter also discusses influences of non-physical conditions such as market access, socioeconomic factors, and differential adaptive capacities among the two groups. Potential mitigation strategies and policy options for assisting maize producers, particularly smallholder subsistence farmers coping with drought, are reviewed. Possible government action to help assuage drought impacts are identified, including promotion of awareness, avoidance, rehabilitation and the enhancement of incentives to induce rational private adaptation.

Experience with past droughts catalyzed collective water authority and users' association exploration for more sustainable water resources use. Vahrmeijer et al. present an example in Chap. 14. They analyze the relationship between drought indices, groundwater discharge, and abstraction for human activities with a hydrological modeling approach and simulate the extent to which extraction by upstream users affect groundwater discharge to downstream uses in a river basin for which groundwater is the main water supply source. The chapter discusses how drought episodes experienced in the case study area increased the awareness of water users in the basin of the importance of understanding the relationship between the extent of abstraction of groundwater and its yield to downstream uses. This induced awareness triggered dialogue among authorities and user groups about how to invest in arrangements to conserve, and equitably manage and sustain, their finite groundwater supplies. The chapter concludes with discussion of how the model developed and employed to conduct the hydrological analysis of these relationships can be used to assist with promoting desired water use and allocation regimes in such a situation.

Hassan (Chap. 21) discusses how drought experiences over the past few decades in South Africa have influenced major reforms to the country's drought management strategies and policy. The chapter explores two key factors in moderating the impacts of drought in South Africa, namely (1) the water supply and management system and its infrastructure, and (2) the policy and institutional environment in place. Hassan distinguishes between two drought management strategies in South Africa—agricultural and hydrological drought (AD and HD, respectively)—as each type is the responsibility of different agencies within government whom adopt different approaches and mechanisms.

The chapter provides a comprehensive assessment of how both AD and HD have been dealt with in South Africa prior to 1980 and thereafter when major revisions were made to key national drought management strategies. Measures and policies adopted prior to 1980 when AD was managed as an abnormal disaster event requiring emergency government assistance (which mainly covered the livestock sub-sector in areas declared as disaster drought areas) are reviewed. The chapter identifies shortcomings of this reactive approach and the difficulties encountered that rendered this strategy ineffective in retarding the degradation of key resources, including land used for grazing and water. A comprehensive review is then provided of the important policy improvements and measures introduced in the 1980s to discourage overstocking and to reduce the pressure on the natural resource base, particularly land used for grazing and water resources.

One of the most important strategic measures South Africa has used to manage drought, especially HD, is the development of an extensive inter-basin water transfer and storage infrastructure to adapt to the arid conditions and high inter-temporal and spatial variations in rainfall patterns that characterize South Africa's climate. This enabled water management authorities to command and regulate surface water flows and provide supplementary irrigation to mitigate drought impacts in water stressed regions. The chapter assesses the effectiveness and weaknesses of the principles guiding this approach and identifies potential areas of improvement. The chapter also examines the recent drought management strategy reforms that aim to promote a more proactive approach of self-reliance in coping with and adapting to drought risks as an integral part of regular farm management and planning.

Problems and challenges remaining with current drought management strategies are then identified and suggestions for better measures and policy changes for more effective drought mitigation that reduces resource degradation are given. Most important among those, and the focus of the chapter, is the potential for using economic policy instruments in drought management, instruments which are currently minimally employed. Recently introduced reforms advocate a strategic shift from short-term drought relief to more important long-term goals of drought risk management, but make little use of economic policy instruments to induce self-reliance, and sustainable farming, water, and land use practices. The chapter identifies areas where there is potential for economic policy measures that would alter the structure of economic incentives in favor of desired changes in planning and management decisions of individuals and communities affected by drought risks.

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Part I

Agronomy, Irrigation Technology, and Water Supply

Chapter 2
Adapting Irrigated Agriculture to Drought in the San Joaquin Valley of California

James E. Ayars

Abstract *Webster's* dictionary defines drought as a continuous state of dryness but does not define a cause for that dryness, just the existence. Irrigated agriculture is in a continuous state of drought by definition, simply because water is supplied by stored surface or groundwater supplies. This results in agriculture being in constant competition for that supply with municipal, industrial, and environmental uses—any one of which may have a higher right to the water supply than agriculture. Thus, even in times of plentiful water supply, a drought condition still could exist in irrigated agriculture. The challenge for agriculture is how to improve water productivity to compensate for any potential losses to competing demands. This chapter presents options for improved water productivity; including changing irrigation systems, improving use of water and fertilizer, and employing irrigation water management strategies, including deficit irrigation. Alternative water management strategies will be discussed, including defining production goals based on the available water supply, integrated water management of irrigation and drainage systems, cropping alternatives, and physical management of crops (e.g., pruning and thinning).

2.1 Introduction

Climate change and global warming are currently among the most discussed and researched environmental concerns throughout world. The effect of these phenomena on the hydrologic cycle is not well understood and, thus, the impact on future water supplies is unknown. Sustained drought is certainly one scenario resulting from global warming, and those areas of the world relying on stored

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water from rainfall runoff and snowmelt as the principal supply are facing an uncertain future (www.epa.gov/climatechange/basicinfo.html).

Drought is simply a prolonged period of dryness with no causal relationship, with potential causes being physical, regulatory, or any combination of these. In arid areas when water supply derives from melting snowpack, below-average snowpack over several years will result in reduced runoff and storage and, subsequently, reduced or no allocations to municipal and agricultural uses. In addition to the lack of water, regulatory restriction on the removal of water from a region or mandates to allocate more water to meet environmental demands can result in reduced or severely limited quantities of water for alternative uses.

California experiences intense competition for water among its urban, agricultural, and environmental interests because the state's water supply depends on the Sierra Nevada snowpack and a series of reservoirs to store the runoff from snow melt. Urban areas in Southern California rely on water transported the length of the state from reservoirs in Northern California. Other users of water stored in Northern California include agriculture on the west side of the San Joaquin Valley (SJV) and the Sacramento-San Joaquin River Delta, recently identified as the most significant estuary on the West Coast of the United States. The delta has a significant water demand for agriculture, recreation, and environmental restoration. The delta is also a critical component in the north to the south transport of water in California, and environmental regulations control the flow through the delta (CVPIA 1992). These regulations determine the volume required to flow through the delta for environmental purposes and the allowable pumping of water from the delta to the San Luis canal that carries water to Southern California. This multiple-use doctrine results in an on-going conflict between the water users with regard to the allocation of water (www.water.ca.gov/swp/delta.cfm).

Drought is an existing condition in California and will become a larger problem as the population of the state increases to more than 50 million people by 2050. In the past century, California has experienced four drought periods prior to the current drought from 2007 to 2009: 1929 to 1934, 1976 to 1977, 1987 to 1992, and 1999 to 2002. There have been several instances of a one-year below-average snowpack but only a few with multiple-year deficits. The drought extending from 1976 to 1977 resulted in less than 37 % of the average Sacramento Valley runoff for the period 1901–1996. The average runoff for this period in the San Joaquin Valley was 26 % of the average for the period 1901–1996.

In 2009, after three years of below-average snowpack in the Sierra Nevada in Northern California, the reservoir levels in the Central Valley Project (CVP) were reduced to critical levels and water supply to agriculture on the west side of the San Joaquin Valley was curtailed, due in part to pumping restrictions and in part to low water supply. The pumping restrictions were a result of the finding that the Delta smelt, an endangered species, was being harmed by the pumping of water from the delta to the San Luis canal for transport to agricultural users in the San Joaquin Valley and to municipal users in Southern California (WSJ 2009). In total, more than 200,000 ha of irrigated land in several irrigation districts were impacted by the lower water supplies from the Central Valley Project. Most of this area is planted with annual crops but there are significant areas of trees and vines located in the affected irrigation districts.

While much attention was given to the plight of farmers on the west side of the valley, the east side farmers experienced little or no restriction in water use. There were adequate supplies from the dams in the state water project that supply water to east side water districts. Also, east side farmers rely heavily on groundwater as either the primary or supplemental supply and are thus not affected by the reduced snowpack or environmental constraints. Agriculture on the east side is dominated by perennial crops, which, as mentioned above, were not affected by water shortages in 2009.

A major difference in the water supply situation between the east and west sides of the San Joaquin Valley is the quality of the groundwater. The groundwater on the east side has a low electrical conductivity (EC < 0.1 dS/m) and is within 100 m of the ground surface. Water of this quality is suitable for all crops and does not present a hazard for soil salination. This is in contrast to the wells on the west side of the San Joaquin Valley that are typically in excess of 500 m deep with groundwater having an electrical conductivity of 1.0–1.5 dS/m and a boron content of 5–10 mg/L. This poor-quality water limits the crops that can be grown and the amount that can be used to simply sustain crop growth, albeit with negative impacts. Perennial crops are generally sensitive to salt and boron, and the groundwater found on the west side can only be used for a limited time to sustain crop production. As a result, good-quality surface water is critical to sustain irrigated agriculture on the west side of the San Joaquin Valley.

The situation in the San Joaquin Valley is unique. That is, while the drought is regional, only a relatively small area is impacted compared to the typical scenario that includes extensive land areas suffering from the lack of water. Yet while the area is small geographically, the impact is significant because of the high agricultural productivity of the affected region. Economic losses in the Central Valley due to the drought were estimated to be $710 million in 2009 (RMN 2009) .

The objective of this chapter is to highlight the management alternatives to sustain water productivity in semi-arid irrigated areas, e.g., the San Joaquin Valley, both in times of adequate water supply and during periods of drought.

2.2 Coping with Reduced Water Supply

A critical part of developing water management strategies is to understand the reality of crop production from the standpoint of the water requirement to meet production goals for a particular crop (e.g., with a forage crop the goal will be biomass, while in tree and vine crops it would be individual fruit). A reduction in applied water for alfalfa, for instance, will result in reduced yield, while a similar percentage reduction in water applied to peaches may result in the complete loss of yield.

The yield—evapotranspiration relationship (Eq. 2.1) has been characterized by many researchers as:

$$1 - (Y_c/Y_m) = K_y(Et_c/Et_m) \tag{2.1}$$

where Y_c is the crop yield resulting from crop evapotranspiration (Et_c). Y_m is the maximum yield related to the maximum evapotranspiration (Et_m) for a given crop cultivar, climate and conditions of the experiment; K_y is a regression coefficient. The relationship has been further refined to consider yield responses resulting from deficit irrigation at strategic periods in the growth cycle. This basic relationship can be further modified when salinity tolerance is considered. The Maas-Hoffman equation (Maas 1990) has been used to describe the relative yield response of plants to uniform salinity in the root zone, and is given as

$$Y/Y_m = 1 - B(EC_e - A_s) \tag{2.2}$$

where Y is the yield, Y_m is the maximum yield, EC_e is the average salinity in the root zone, B is the slope of the yield reduction with a 1 dS/m increase in the average soil salinity in the root zone, and A_s is the threshold where yield begins to decrease with increased salinity in the root zone.

Passioura (2006) discusses the objectives of water management with limited water supply in the context of grain crops grown in rain-fed agriculture. The goals are to transpire more of the limited water supply (Eq. 2.1); improve exchange of transpired water and CO_2; more effectively produce biomass; and convert biomass into grain or other harvestable material. To do this, he suggests several approaches that are applicable to irrigated agriculture as well. In regions with winter rainfall, soil and crop residue management will be important to improve infiltration and provide soil water storage. Timeliness of operation, ensuring evenness of establishment, and nutrient management will contribute to improved yield potential. Water supply management to reduce evaporation and surface runoff, and deep percolation losses is another important consideration.

Irrigation water management depends on the crop selection, the irrigation system, and the production goals. The importance of each of the components will be determined by the available water supply. When water is plentiful, any crop can be selected and the type of irrigation system used and its management are not given much consideration. As the water supply dwindles, crop selection is more focused and irrigation system efficiency is a prime concern. With abundant water, the production goal may be to maximize yield; conversely, with limited water it may be to break even or make some amount of profit. The challenge is to weigh the factors to determine the appropriate mix of cropping, irrigation system selection, and management to achieve the desired production goal. The following sections will discuss the water management implications relative to the selection and management of both crops and irrigation systems.

2.2.1 Crop Selection

Factors included in crop selection include the water requirement, the salt tolerance, and the seasonal growth period. The total crop water requirement will be an easy selection criterion (e.g., does it require 500 or 750 mm of water to be productive). Another consideration will be whether the total water supply can be met in part by rainfall. In the SJV, rainfall occurs primarily during the late fall, winter, and early spring, which means that crops grown using rainfall to supplement irrigation have to be suited to cool weather. The crop selection then is focused on vegetable crops (e.g., lettuce, broccoli, onion, all of which are short-season and cool-weather tolerant).

An alternative would be to develop a dry land production strategy that uses stored soil water and rainfall to produce a crop. This is typically done with a grain crop planted in the early winter that relies on winter rain for production. A decision can be made in the spring to provide irrigation to complete the crop or to accept yield losses and let the crop mature on existing soil water. This provides a money-making opportunity with little expenditure. Depending on the outcome from rainfall and the projected water supply, spring and summer cropping can be developed.

The salt tolerance of the crop will also be a factor in the crop selection. Many of the vegetable crops are salt sensitive and require good-quality (low-salinity) water for germination and growth. Field crops may be more salt tolerant than vegetable crops but have longer growing seasons and higher water demands. If both good- and poor-quality water are available, cropping pattern and irrigation management can be developed to incorporate both supplies (Rhoades 1989; Rhoades et al. 1989). When using saline water for irrigation, salt management in the soil profile is critical to limit salt accumulation in the root zone. While this may not be a problem the first year, over a period of extended drought surface salt accumulation may impact germination of subsequent crops. Future salinity management will require additional good-quality water for leaching.

Another factor in the cropping selection is the total economic return and its relationship to productivity. The concept of crop-water production function needs to be included in the discussion of crop selection and management. The crop-water production function is described as the crop yield and the applied water used to produce it. The shape of the curve will reflect the over or under irrigation of the crop. As noted previously, yield is nearly a linear function of the evapotranspiration—when the yield is related to the applied water, the deviation of applied water to the crop requirement results in a non-linear response. Singh et al. (1987) substituted evapotranspiration for applied water and obtained a non-linear response for wheat that is demonstrated in Fig. 2.1. Crop water production curves are also impacted by water quality as well as the depth of applied water. As the electrical conductivity increases, additional water is applied to provide a leaching fraction to control soil salinity. The additional water does not provide a proportional increase in yield, which results in a non-linear response.

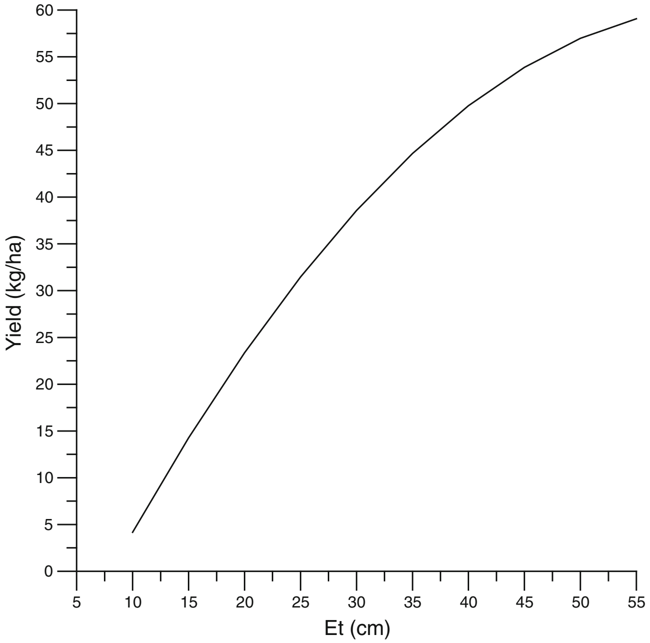

Fig. 2.1 Typical crop-water production function after Singh et al. (1987)

The term water productivity and water use efficiency are used to describe yield as a function of applied water. In the case of deficit irrigation, the water productivity or efficiency can be high because of deficit irrigation. High water productivity does not necessarily correspond to maximum yield, since the yield function is not linear in relation to applied water. As yields are maximized, the return on applied water is reduced, so the maximum water productivity may not be at maximum yield. Most farmers do not operate with that set of criteria, since the yield response curves may not be well defined and this requires an additional level of management.

The interactions of water and fertilizer on yield are not well researched. Phene et al. (1986) demonstrated significant increases in water productivity of tomatoes when nitrogen, phosphorous, and potassium were added to the irrigation water and the crop water requirement was met. These increases were a result of the fertilization, not additional applied water. Thus, in a water-short year, fertilization may be used with a deficit-irrigation strategy to maintain production sufficiently to remain economically viable. Knapp and Schwabe (2008) demonstrated how efficient nitrogen management varies with water applications and irrigation efficiencies in the case of corn within a spatial dynamic model.

It is possible to develop a cropping sequence that effectively uses the available water supply to produce crops at less than maximum or even optimum yields, but results in a better net return than can be achieved by using the total supply on a single crop. This strategy requires the manager to develop a yield and input strategy that optimizes the inputs of seed material, fertilizer, applied water, soil water, and labor. It can be very effective if rainfall is included as part of the strategy. This concept needs additional research.

2.2.2 Irrigation System Selection

A goal in irrigation management is to achieve a high value of irrigation efficiency, which is a performance parameter that describes the ratio of the beneficially used water and the water applied to a field. Beneficial uses include evapotranspiration, cooling, frost protection, and salt management—not just Et_c. This means that there will be some losses to deep percolation needed for salinity control to maintain productivity. The objective of the system design and operation is to control the losses to what is needed and to distribute the losses uniformly across the field. The distribution uniformity (DU) is the measure used to describe the water lost to deep percolation from irrigation. Typically, surface systems, (furrow, border) are assumed to have the poorest DU's because the infiltration is controlled by the soil surface and the length of time water is on the soil surface. With surface irrigation, there is potentially a large difference in infiltration opportunity time between the head and tail ends of the field. Aggressive management can minimize the differences. This type of distribution non-uniformity is generally not present in properly designed and operated pressurized systems since water is delivered across the field in a pipe.

Improved irrigation efficiency is generally assumed to be associated with selection of advanced irrigation equipment, e.g., switching from surface irrigation methods to pressurized systems. This is true to some extent, but simply buying a new sophisticated irrigation system does not lead to improved water management unless significant effort is made to use this system properly. An often overlooked factor in irrigation system design and management is the selection and design of a system to fit the conditions, e.g., the soil type, field size, source of water, available water supply, management skill, and crops. Unless these factors are considered, there is no guarantee of improved irrigation efficiency and productivity.

In the SJV, the majority of the cropping is field crops (e.g., tomato, cotton, melons), which have typically been irrigated using surface irrigation that is ideally suited for the valley conditions due to the existing clay loam soils with gentle slopes. The lower cost of the system has made the existing cropping profitable. Irrigation efficiency ranges from 75 to 85 % with good management. Hand-move sprinkler systems are also used for germination and some seasonal irrigation (Ayars 2003). These systems are capable of better irrigation efficiency than surface irrigation (Hanson and Ayars 2002). However, labor costs are a limitation with using hand-move sprinklers.

A shift from either surface or sprinkler system to micro-irrigation systems was generally not considered because of the additional cost of the micro-irrigation system. The cost of surface irrigation is in the range of $185 to $370 per ha, while a micro-irrigation system can cost up to \$3,700 per ha. Also, micro-irrigation systems were not generally suited to field crops. The transition from surface to pressurized systems has been driven by reduced water availability and reduced labor availability.

There has been extensive adoption of subsurface drip irrigation (SDI) on tomatoes and vegetable crops (lettuce, peppers, broccoli) being grown on the west side of the SJV. Tomato yields were improved by nearly 20T/ha when converting from surface to SDI. This was a result of being able to match the crop water demand and to apply fertilization to meet crop requirements. The adoption also has been facilitated by improvements in the drip tape size that permitted longer lateral lengths (300 m) and development of equipment to install and retrieve drip tape. Additionally, the use of differential global positioning systems to guide the tractor during the installation of the drip tubing has enabled improved cultivation in fields with permanently installed tubing.

Labor constraints along with reduced water supplies have resulted in a reconsideration of the use of center pivot sprinklers in the SJV. Center pivots and linear move irrigation systems were tried in the 1980s and 1990s with very little success. The soils on the west side of SJV are clay and clay loam soils with low-infiltration rates; consequently, the early machines were not designed to keep water off the wheel tracks so that ponding occurred which resulted in machines getting stuck (Ayars et al. 1991). Current designs are using spray packages that reduce application rates and also keep the wheel tracks dry.

Well-managed micro-irrigation and sprinkler systems have the capability to match crop water use and fertilizer requirements at high levels of irrigation efficiency. The added benefit is that deep percolation losses are significantly reduced, which reduces the drainage disposal problem found on the west side of the SJV (Ayars 1996). SDI has been demonstrated to be effectively used in crop production in the presence of shallow groundwater without the need for subsurface drainage (Ayars et al. 2001; Hanson et al. 2006).

2.2.3 Water Management

Water management will be a critical component in coping with reduced water supply. The first step in improved water management is to implement irrigation scheduling to provide water when and in the quantities needed by the plant. This is routinely done using an evapotranspiration-based approach where the crop water use is determined based on the climate and stage of plant development. The equation is

$$Et_c = K_c * Et_o \tag{2.3}$$

where $\mathrm{Et_c}$ is the crop evapotranspiration, $\mathrm{Et_o}$ is the reference crop potential evapotranspiration, and $\mathrm{K_c}$ is the crop coefficient that is a function of the plant development. The product of Et_o and K_c is the crop evapotranspiration Et_c or the crop water use during a specified time. The irrigation schedule is constructed by accumulating the water use (Et_c) until a predetermined threshold value of water lost is reached at which time irrigation is initiated to replace the lost water. The threshold is developed based on the age of the crop, and the soil's water-holding capacity, and the allowable depletion of the soil water. An alternative method is to operate on a high-frequency schedule in which the goal is to supply water on a nearly daily basis. In this case, soil water storage is not a critical component in the scheduling methodology and an accurate measure of the water loss is required.

The accumulated plant water use from soil water is then replenished to sustain the plant development with minimum stress. The depth of irrigation will be equal to the lost water. This value will be adjusted to account for the efficiency of the irrigation system. The adjustment for efficiency will attempt to minimize the yield lost to deficit irrigation in parts of the field due to distribution non-uniformity. The irrigation frequency will depend on the soil type, the irrigation system, the crop growth stage, and the susceptibility of yield loss to water stress.

Soil type affects the amount of stored soil water, with sand having a lower storage potential than loams and clay soils. With reduced storage, irrigation frequency will have to be increased to limit water stress. The irrigation system operational characteristics determine how frequently irrigation can occur. Surface systems typically apply 75–100 mm of water during each irrigation event, while pressurized systems can apply as little as 10 mm per event. As a result, the pressurized systems are used for high-frequency irrigation (daily), while surface systems are used for weekly or longer irrigation intervals. The effectiveness of this approach relies on a good understanding of the crop water requirements during the growth cycle and adequate climate information.

Extensive work has been done in California to determine the crop water requirements and the development of the crop coefficients needed for irrigation scheduling for a wide variety of crops (Ayars et al. 2003; Ayars and Hutmacher 1994; Grattan et al. 1998; Hanson et al. 2003). The California Irrigation Management Information System (CIMIS) has weather stations located throughout the state that can be used to determine the potential evapotranspiration needed to determine crop water use. In addition to California, Arizona, Kansas, Texas, and Washington State operate weather networks for irrigation scheduling.

One solution for annual crops during water shortages is to forgo planting a crop or, alternatively, attempt dryland agriculture and rely solely on rainfall (e.g., cereal crops). If some water is available, a survival strategy needs to be developed that depends on the total available water. Approaches include production on limited acreage for crops with high-water demand or switching to short-season crops with lower water demand, and use in conjunction with rainfall and stored soil water.

Perennial crops that are currently in production create a different problem because irrigation is necessary. The decision is further complicated by the type of crop, i.e., whether it is a tree or vine crop. The selected strategy will depend on the volume of available water. One strategy will be to opt for an economic level of production on a portion of the acreage and restrict irrigation or stress the remaining acreage.

For tree crops, the time of fruit maturity will also provide some opportunities for water savings. An early maturing crop can be nearly fully irrigated prior to harvest and stressed after harvest with limited impact on subsequent crops. In the San Joaquin Valley, the greatest portion of the Et_c for an early maturing peach crop occurs after harvest (Johnson et al. 1992, 1994).

Two water management strategies have been proposed for controlling plant water stress during reduced irrigation. The first is regulated deficit irrigation (RDI). The concept is that there are periods of growth when the plant can be put under stress without significantly impacting yields, which allows economic levels of production with reduced water requirement. It has been successfully demonstrated on fruit and nut crops (Chalmers et al. 1981, 1986; Johnson et al. 1992; Goldhamer et al. 2006). The RDI strategy as currently practiced provides full water supply during periods of fruit growth development and significantly reduced supply during other periods.

An alternative strategy would be to decrease the water supply over the entire growing season. Implementation of this strategy requires knowledge of the crop water requirement which may not be well defined. Williams et al. (2010) demonstrated that the yield of Thompson Seedless grapes was not affected when grown with a sustained deficit of 80 % of crop water use, measured with a weighing lysimeter. In either case, the water requirements during the production cycles are not well known for most crops.

The second water management strategy is known as partial root zone drying (PRD) (Costa et al. 2007; Kang et al. 2002). This method dries down a portion of the crop root zone while maintaining soil water in the remainder of the root zone and then switches to another section of the root zone. The concept is to induce stress in a portion of the plant supplied by the stressed portion of the root zone, resulting in a chemical signal being sent to the stomata which close and reduce plant transpiration and, thus, total water requirement. This has been implemented using two drip irrigation laterals that were placed on each side of a grape vine, and the irrigation is alternated between each side of the vine. This results in the alternate wetting and drying of the soil with induced stress in part of the root zone. A drawback in this approach is the additional cost due to the extra irrigation equipment. The success of the approach depends on the crop being responsive to the drying down. In soils with large water-holding capacity, there may not be an advantage over regulated deficit irrigation, since there may be inadequate drying of the soil and stress development (Sadras 2009).

Shallow groundwater represents an alternative supply in many arid and semi-arid irrigated areas. When the groundwater is a result of poor irrigation practice, the supply may be limited; there may be situations, however, in which the groundwater is a result of lateral flow from another water source. In this instance, there may be enough supply to develop management practices to use this water (Christen and Ayars 2001). If the area requires subsurface drainage, the drains can be managed to control the water table position to facilitate in situ use by the crop

(Ayars et al. 2007). Crops have the potential to get up to 50 % of the water requirement from shallow groundwater, depending on the groundwater salinity, crop salt tolerance, and depth to groundwater (Ayars et al. 2006). Such an option makes the groundwater a potential valuable resource during droughts.

2.2.4 Agronomy

One approach proposed for crop drought management in perennials is to engage in severe pruning of the tree or vine and lose production for that year. Implementing this strategy with a vine crop may result in just a one-year loss, since vines are heavily pruned every year. Severe pruning of a tree crop may result in a two- to three-year loss of production, since the entire scaffold may be eliminated and it will take several years to regain the structure needed for production.

As Passioura (2006) has indicated, the role of agronomy will be to conserve water and produce the maximum yield possible with the stored supply. One practice is to capture rainfall with tillage to incorporate stubble to improve infiltration and to produce a mulch that minimizes evaporation losses. Precision agriculture will play a role in this system by insuring uniform stand establishment and precision application of fertilizers. Fertilization strategies will be required to manage plant growth and yield based on existing water supplies. The goal would be to prevent luxurious use of fertilizer that would result in vigorous plants that cannot be sustained with the stored soil water and the available irrigation supply. Weed management will also be a part of the strategy, since weeds are a non-beneficial user of water and need to be eliminated.

Surface water management will also be required. The field should be prepared to insure infiltration of rain and to minimize water lost to surface runoff. In irrigated areas, tailwater return pits and other water conservation structures can be used for storage and recycling surface runoff.

Cultivar selection will be important in a drought strategy, since each cultivar will have its own characteristics for water productivity. The harvest index (HI) is a measure of the yield of the crop to the biomass created and is often used to characterize the productivity of a crop (Howell 1990). The higher the index, the greater is the yield relative to the biomass. This demonstrates a partitioning of the transpired water to the fruit and not the biomass, which is a desirable characteristic for the crop.

2.2.5 Alternative Water Supply

In the San Joaquin Valley, the surface water supply is high quality (low salinity) and has no restrictions on use while the ground water quality varies from high quality on the east side to saline (1–15 dS/m) on the west side. In water-short periods alternative supplies will need to be considered, including saline groundwater and treated municipal effluents. A major problem will be in the delivery of this water to the farm. There may be some opportunities for poor-quality water in one area to be mixed into the good supply for transport to another region for use. However, this is limited since this might be part of a municipal supply as well.

Treated municipal wastewater also represents an alternative supply for agricultural use. Extensive research has demonstrated the feasibility of this approach (Angin et al. 2005; Carr 2005; Dugan and Lau 1981; Koo and Zekri 1989). Regulations allow the application of treated waste water to feedstuff for animals and prohibit the direct application to food that will not be processed prior to consumption. One limitation on this supply is access. The infrastructure needed to supply water is generally not in place and, hence, mixing with existing surface supplies for transport via a canal will not be a viable alternative, since that water may also be a municipal supply.

Treated wastewater is currently being used in California for irrigating highway landscape, control of salt water intrusion and in some agricultural enterprises located near cities. The Irvine Ranch Water District (IRWD) in Orange County, California, is currently using treated wastewater on approximately 400 ha of crops. Water produced by IRWD carries an Unrestricted Use Permit from the California Department of Health Services and thus meets the requirements of Title 22 of the State Health Code, which is of high enough quality to be used in swimming pools. The treated wastewater is just one component of the total water supply for the IRWD.

2.2.6 Future Concepts

In the future, irrigated agriculture will have to make every drop of water count and will rely increasingly on poorer-quality water as part of the supply, thereby requiring increased levels of management. Farmers may also be faced with a smaller labor pool, which increases the need for sophisticated technology to control the irrigation systems and the determination of water requirements. Much of the data to accomplish this task has yet to be collected.

The interaction of irrigation and fertilizer management is one area that needs extensive research. Past research has shown the need and effect of fertilizer on crop productivity when fully irrigated, but additional research is needed to determine the effects of fertilization on yield at less than full irrigation. In addition, work needs to continue to define the crop water requirements, since new cultivars are being developed continually.

Decision support systems will need to be developed for crop production based on water productivity. This requires a determination of the crop water production function curve for a range of water management strategies (e.g., sustained deficit irrigation or deficit during particular growth stages). This support system will need real-time feedback of soil water status and plant water use to assist in the irrigation schedule.

Water quality and the effects on soil quality and plant growth and quality will be another area of concern. Traditionally, water quality has been related to salinity and the osmotic effect of increased soil water salinity on plant growth and yield; however, as treated wastewater becomes a potential supply, additional contaminants will have to be considered. Municipal wastewater includes the traditional salts but also the potential for heavy metals and a wide range of pharmaceutical compounds that may have a significant impact on the soil flora and fauna with yet-to-be determined effects on plant growth and quality.

Salinity management has always been a component of water management in irrigated agriculture; however, salt has been approached as something to be eliminated from the soil profile. This is not a viable approach any longer because of the potential for significant environmental damage from the discharge of salt from subsurface drains (Ayars et al. 2007). Salt management in the past required excess amounts of water to remove salt from the crop root zone. Future management must be focused on maintaining the salt in the root zone at a level that will not negatively impact crop production that will require improved monitoring capability and a better understanding of crop salt tolerance.

Salt management also will be impacted by drainage system design and management (Ayars et al. 1997). Implementing new drainage system designs with controls will reduce the total salt load from the system and improve the water management by increasing in situ crop water use. This will require additional technologies for real-time control of the drainage system and development of equipment to retrofit existing drainage systems.

Precision agriculture will play a significant role in the future. The ability to match the crop demand for water and fertilizer and to selectively manage the salt across the field may have a significant impact on productivity and the conservation of resources.

2.3 Conclusions

The population of California is projected to increase from the current approximately 35 million people to 50 million people by 2050. Decisions will need to be made on how to accommodate the water supply needs for this population. In addition to the population, there will be demands for industrial water supply and environmental uses, and the role of agriculture will be questioned. Since agriculture is the single largest water user in the state, it will be the first source to be considered for supply reductions, and questions will have to be answered as to the volume of supply that will be made available. Potential supply reductions will depend on many of the factors discussed above, but also include consideration of the state's ability to develop additional water storage and the type of storage. The options are to build additional reservoirs, increase the size of existing structures when possible and/or conjunctive use (groundwater recharge). Any solution will require a large investment; the investment will depend on the water demand and what policy decisions are made with regard to the extent of the agricultural enterprise in California.

Another factor in the decision is the impact of California agriculture in the food supply system within the United States and the world. California supplies nearly 100 % of the production of several commodities in the United States, and loss of this production will have implications with regard to food security and food costs. Economists argue that water will provide a larger return when used in production of silicon chips and thus that may be a better use of water from an economic view. However, economics cannot be the single consideration in this instance.

If a decision is made to sustain agriculture, it will probably be with a mixture of high-quality water and impaired water from saline groundwater and municipal sources. In this instance, there will need to be infrastructure developed to implement this strategy. This will require transporting water from a municipal site to a storage and distribution facility that is accessible to the agricultural community. Another alternative may be the "toilet to tap" concept where municipal water is treated to a level that makes it suitable as water supply. While technically feasible, this is an alternative that is not currently politically acceptable.

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Chapter 3

Impact of Drought on Adelaide's Water Supply System: Past, Present, and Future

Holger R. Maier, Fiona L. Paton, Graeme C. Dandy and Jeffery D. Connor

Abstract Adelaide, the capital of South Australia, has a population of approximately 1.3 million. In wet years, Adelaide obtains most if its water supply from the nearby catchments in the Adelaide hills. However, in dry years, about 90 % of Adelaide's water supply needs are met by water that is pumped from the River Murray. Severe drought in the Murray-Darling Basin in the recent past has meant that the security of Adelaide's water supply has been threatened. In response, strategies for securing Adelaide's water supply into the future have been developed, including diversification of water sources and demand management strategies. A case study of the performance of the southern Adelaide water supply system under various supply scenarios has been conducted. This highlights the importance of the use of stochastic analysis, risk-based performance measures and extensive scenario analysis in order to enable the long-term planning of water supply systems in hydrologically variable and uncertain environments, rather than having to react to drought events.

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3.1 Introduction

Adelaide is the capital city of South Australia (Fig. 3.1) and has a population of approximately 1.3 million. It is often described as having a “Mediterranean” type climate, with mild winters and dry, hot summers. Adelaide’s maximum daily temperatures range from approximately 15 °C in July to 29 °C in January and its hydrologic regime is highly variable, with recorded annual rainfall totals ranging from 257 to 882 mm. Adelaide’s annual rainfall exhibits a distinct west to east gradient, with average annual rainfalls ranging from 450 mm in the Adelaide Plains to 650 mm in the Mount Lofty Ranges.

Due to Adelaide’s highly variable hydrologic regime, a significant amount of storage is required in order to provide a reliable water supply. From 1873 to 1983, 10 major storage facilities, with a total capacity of ~198 GL, were constructed for the purpose of securing Adelaide’s water supply. From 1892 to 2006, inflows into these storage facilities varied from ~20 to ~670 GL. Over time, the water available from the local catchments in the Mount Lofty Ranges was found to be insufficient to support the city’s population growth. Consequently, two major pipelines were constructed to supplement Adelaide’s water supply by pumping water from the River Murray to Adelaide, one from Mannum and one from Murray Bridge (Fig. 3.1). In an average year, the amount of water supplied from the River Murray is ~80 GL (approximately 40 % of Adelaide’s annual water consumption), but this can increase to 180 GL (approximately 90 % of Adelaide’s water consumption) during a dry year.

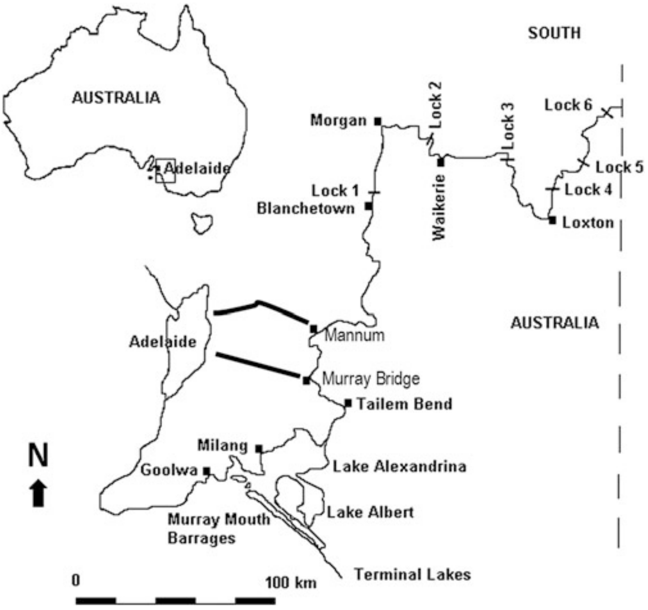

Fig. 3.1 Location map

The response of the relevant authorities to periods of below-average inflows in Adelaide's local catchments and those in the River Murray (since the construction of the two water supply pipelines) is discussed in the next section for three distinct periods: past (prior to 2002), present (2002–2009), and future (2010 onwards). In the subsequent section, a case study is presented, in which the future performance of the southern Adelaide water supply system is assessed for a number of water supply option scenarios.

3.2 Responses and Adaptations: Past, Present, and Future

3.2.1 Past Response (Prior to 2002)

In the period prior to 2002, the approach taken for securing Adelaide's water supply was a combination of increasing storage capacity and utilizing the River Murray as a new source of water. The first reservoir at Hope Valley was completed in 1873, followed by Happy Valley reservoir, which was constructed from 1892 to 1897 (Fig. 3.2, Table 3.1). No inflow records are available prior to the construction of these reservoirs, making it impossible to ascertain whether construction of these reservoirs followed low-flow periods. However, it is evident from Fig. 3.3 that construction of the next four reservoirs (Barossa, Warren, Millbrook, and Mount Bold) commenced following a number of years of below-average inflows. While it must be noted that the reasons for the commencement of construction of these reservoirs is likely to be affected by a number of related factors, such as long-term planning and population growth, in addition to the occurrence of dry spells, the decision to construct these reservoirs appears to be at least in part a response to periods of below-average inflows.

This pattern of responding to low-flow periods with the implementation of major water supply infrastructure projects continued in the 1940s and 1950s, with the construction of the South Para reservoir and the first pipeline from the River Murray, following an extended spell of low inflows. Figure 3.3 shows the extended dry spell prior to the construction of the Mannum to Adelaide pipeline, which included 13 out of 17 years during which inflows were below-average. This resulted in the realization that the yield from the local catchments in the Adelaide hills would not be sufficient to provide a long-term, reliable water supply for Adelaide during times of drought. As a result, the 60 km long Mannum-to-Adelaide pipeline was constructed, which enabled the River Murray to be utilized as an additional source of water supply for Adelaide.

Myponga reservoir was built between 1959 and 1962, following several years of highly variable inflows. Construction of a second pipeline from the River Murray commenced in 1968 after a number of years of below-average inflows, which culminated in the imposition of voluntary water restrictions in Adelaide in 1967. The 48.6 km long Murray Bridge to Onkaparinga pipeline was completed in

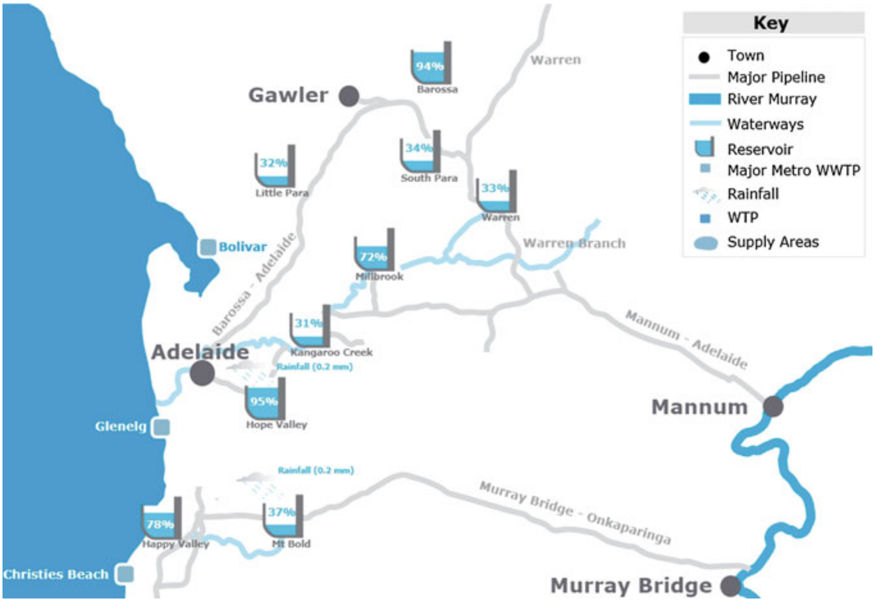

Fig. 3.2 Adelaide water supply system—local reservoirs and River Murray pipelines (modified from SA water website http://www.sawater.com.au/SAWater/WhatsNew/WaterDataUpdate/ReservoirHome.htm?ReservoirSystem=Metro. Accessed 11 Mar 2013)

1973. In subsequent years, two additional reservoirs were constructed (Little Para and Kangaroo Creek), increasing Adelaide's total storage capacity to 198.5 GL (Fig. 3.2).

Since the completion of Kangaroo Creek reservoir in 1983, Adelaide was considered to have a very secure water supply. While the reservoirs were only capable of holding about one year's supply of water, Adelaide was considered to have a "guaranteed" source of water from the River Murray that could be used to fill the reservoirs as needed. This is because water-sharing arrangements with upstream states ensured South Australia would receive agreed "entitlement flows" every month of the year, even during times of low flow in the South Australian reaches of the River Murray. These flows were generated by releases from Lake Victoria, a large storage facility near the South Australian border upstream of Lock 6 (Fig. 3.1).

It should be noted that during the 1990s, alternative water sources using stormwater and recycled wastewater were also developed (Table 3.1), which produced approximately 25 GL of non-potable water per year. However, the primary motivation for the development of both of these water re-use schemes was concern about pollution of the Gulf Saint Vincent (the receiving water body for both stormwater and treated wastewater) rather than water supply security.

The stormwater re-use scheme was developed by local government authorities in Salisbury, which is north of Adelaide. Wetlands were constructed in order to

Table 3.1 Major water supply infrastructure prior to 2000

Years	Source	Capacity (ML)
1873	Hope Valley reservoir	2,840
1892–1897	Happy Valley reservoir	11,600
1899–1902	Barossa reservoir	4,515
1914–1916	Warren reservoir	4,790
1914–1918	Millbrook reservoir	16,500
1932–1938	Mt Bold reservoir	46,180
1949–1958	South Para reservoir	45,330
1951–1955	Mannum-Adelaide pipeline (River Murray)	138,700[a]
1959–1962	Myponga reservoir	26,800
1968–1973	Murray Bridge-Onkaparinga pipeline (River Murray)	187,610[a]
1974–1977	Little Para reservoir	20,800
1982–1983	Kangaroo Creek reservoir	19,160
1994	City of Salisbury stormwater reuse schemes	5,000[b]
1999	Virginia irrigation project (recycled wastewater)	~20,000[b,c]

[a] Total pipeline capacity, although the maximum amount delivered over a 5-year period in accordance with the prevailing water licensing agreement is 650 GL (130 GL per year on average) for both pipelines combined

[b] Non-potable supply

[c] This does not supply Adelaide proper, but market gardens in the peri-urban area

treat stormwater before discharging it to the sea. However, testing of the treated wetland water indicated that its quality was sufficient for non-potable re-use. As a result, a number of aquifer storage and recovery (ASR) schemes were developed, as part of which treated water from the wetlands is stored in local aquifers before being extracted for re-use. At the time of writing, the ASR schemes produced about 5 GL of non-potable water supply each year.

The wastewater re-use scheme was developed to prevent the discharge of secondary treated wastewater into the sea, as high levels of nutrients in the discharge caused the destruction of seagrasses and mangrove forests, as well as toxic algal blooms, and to serve the growing water supply needs of horticultural regions to the north of Adelaide. An 18 km long pipeline was constructed from the wastewater treatment plant at Bolivar (Fig. 3.2) to the township of Virginia, from which water is distributed to more than 200 irrigators who grow mainly vegetables. In order to ensure the treated wastewater is of acceptable quality, the treatment plant uses a dissolved air flotation filtration (DAFF) process.

3.3 Present Response (2003–2009)

3.3.1 Water Proofing Adelaide Strategy (2005–2025)

In the period between the completion of the second pipeline from the River Murray in 1973 and 2002, Adelaide's water supply was very secure, despite a large

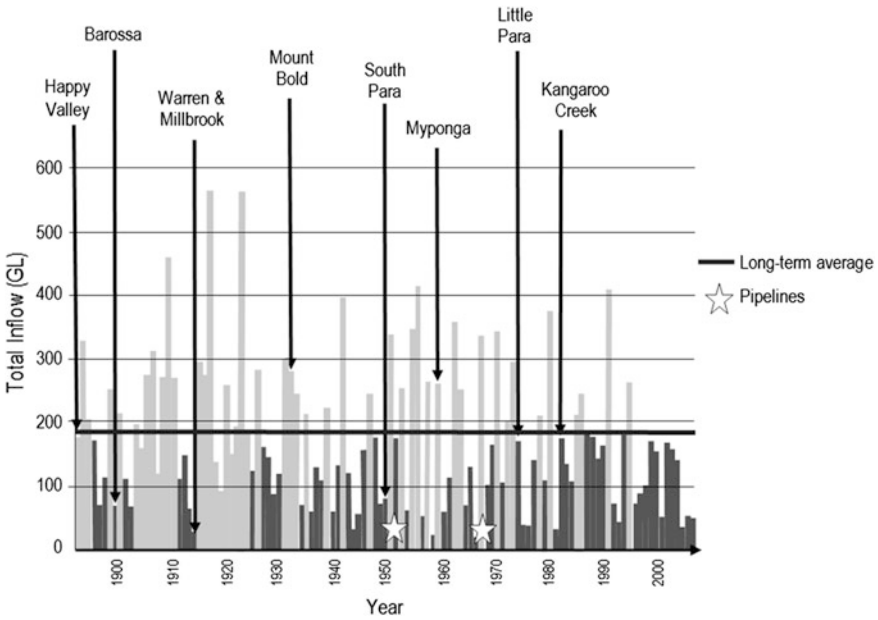

Fig. 3.3 Inflows into Adelaide's water supply reservoirs and commencement times of major water supply infrastructure

number of years of below-average inflows from the local catchments in the Mt. Lofty Ranges from 1987 onwards (Fig. 3.3). This was because during this period, flows in the Murray-Darling system were above average (Fig. 3.4), thereby enabling sufficient water to be pumped from the River Murray to meet Adelaide's water supply.

However, this situation changed with the recent drought in the Murray-Darling Basin, which commenced in 2002 (Fig. 3.4). The combination of low flows in both the River Murray and local systems resulted in the introduction of compulsory water restrictions in Adelaide in 2003 and prompted the development of the Water Proofing Adelaide Strategy (South Australian Government 2005), which was released in 2005. The goal of the strategy was to ensure that Adelaide was "waterproofed" until 2025. Although development of the strategy was in response to water shortages, as were all of the previous efforts of increasing Adelaide's water supply security discussed above, it represented an attempt to engage in longer-term, strategic water resources planning in relation to Adelaide's water supply, rather than responding to "crises" once they had occurred.

As part of the strategy, a wide range of issues in relation to supply and demand were considered. However, only a small number of these were recommended for action. In order to establish a baseline scenario, the strategy considered an increase in Adelaide's population from 1.3 to 2 million by 2050, as per the goals in South Australia's strategic plan, a reduction in available water for water supply purposes

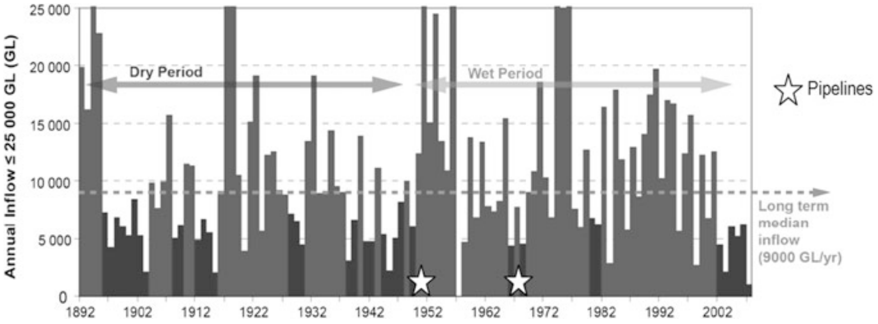

Fig. 3.4 Inflows into Murray-Darling system (Adapted from Young and McColl 2008)

due to environmental water needs and a reduction in water availability due to climate change. It should be noted that no detailed climate change analysis was conducted. Instead, a 10 % reduction in annual inflows in local catchments was assumed to occur due to climate change by 2025, referenced by "best information currently available" (South Australian Government 2005). Based on these assumptions, it was concluded that by 2025, Adelaide's water supply would have an annual shortfall of 40 GL during drought years.

In terms of strategies for increasing supply, a wide range of alternative water sources was investigated, such as buying water from the River Murray, cloud seeding, domestic aquifer storage and recovery, greywater recycling, icebergs, large-scale water supply schemes, localized wastewater recycling, on-site wastewater treatment/reuse, seawater desalination, and sewer mining. However, the conclusion was that most water sources other than those currently used were uneconomic and/or would result in adverse environmental impacts and were therefore not considered, although desalination was flagged as a potential future water supply source. There were targets to increase supply of stormwater and rainwater to 20 GL and the supply of recycled wastewater to more than 30 GL by 2025. However, there were no details of specific schemes, other than a requirement for all new dwellings to have rainwater tanks plumbed into the house. Consideration also was given to loss reduction and a number of specific actions were identified, including covering open channels or replacing them with pipes to reduce evaporation losses, as well as leakage reduction in the reticulation system.

As part of the Water Proofing Adelaide plan, the major approach to addressing the 40 GL-per-year shortfall was to reduce average annual demand by 35 GL by 2025. The strategies for achieving this included a mixture of permanent water conservation measures, the introduction of a nationally recognized water efficiency labeling scheme (WELS) and public education programs. However, water conservation measures that prohibit outdoor watering at times when evaporation losses would be high were the only "compulsory" approach to demand reduction. All other strategies relied on voluntary responses from consumers. Pricing policies also were considered, but no changes to the current system were recommended. The report concluded that if the measures suggested in the report were implemented, the maximum annual shortfall would be 5 GL, which could be managed by the use of temporary water use restrictions.

Given the high natural variability of the hydrologic regime in the Murray-Darling Basin, coupled with the uncertainties surrounding climate change predictions, it is somewhat surprising that there was a lack of stochastic analysis and use of risk-based performance measures to underpin the strategies presented in the Water Proofing Adelaide plan, particularly since the water security of more than 1.3 million people was at stake. The assumption that water from the Murray would be a reliable source well into the future without any analyses of the impact this would have was a notable omission. Finally, the lack of definitive strategies that address both the demand and supply of Adelaide's water security also was surprising.

3.3.2 Water for Good Plan (2009–2050)

The Water Proofing Adelaide Strategy was released in 2005 and despite the report's conclusion that "…implementation of the Water Proofing Adelaide strategy will provide sufficient mains water to meet Adelaide's needs, even in a drought year, well beyond 2025" (South Australian Government 2005), it was rather short-lived. The major catalyst for this was the ongoing drought in the Murray-Darling Basin, with inflows that were some of the lowest in recorded history (Fig. 3.5). In response to these low flows in the River Murray, the South Australian government introduced temporary water restrictions, in addition to the permanent water conservation measures introduced as part of the Water Proofing Adelaide Strategy. Some of these included a ban on the use of sprinklers for outdoor watering, and watering with a hand-held hose for a maximum of three hours per week during a six-hour designated weekly window. This had a significant impact on people's behavior and also had a visible public impact, as many public fountains were turned off and public parks turned "brown." In addition, the government introduced rebates on water-saving devices, such as water-saving showerheads and front-loading washing machines, in an attempt to provide stronger incentives for the adoption of some of the strategies in the Water Proofing Adelaide plan, rather than simply relying on education campaigns.

As a result of the water restrictions, and the direct impact they had on peoples' lives, there was much community discussion about Adelaide's water supply problems and a strong feeling that the government should address the problem once and for all. Issues that were discussed included alternative sources of water supply, particularly stormwater re-use and desalination. The state government's response was to commission a 50 GL per year desalination plant, which was upgraded to a 100 GL per year plant soon after. This resulted in further public debate about the relative merits of desalination, particularly the likely environmental impacts due to brine discharge into the ocean and energy requirements. Cost was considered less of an issue, as there seemed to be an increased public

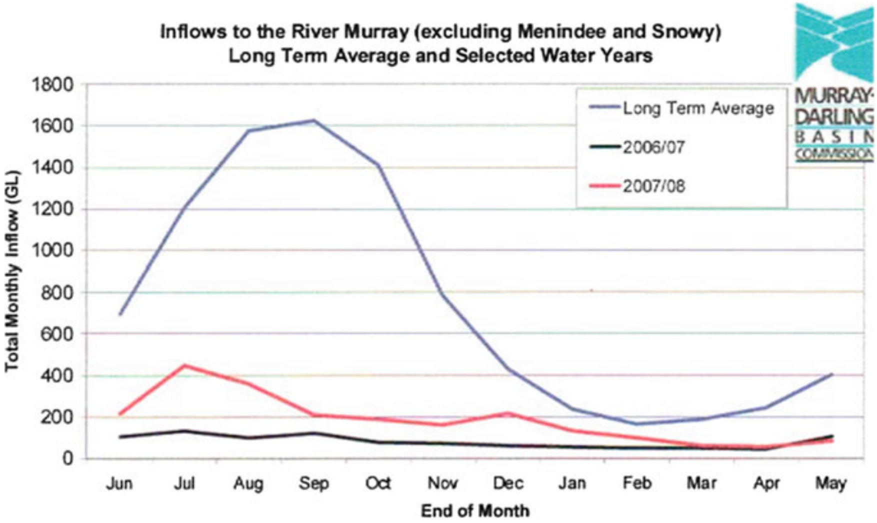

Fig. 3.5 Seasonal inflows into Murray-Darling Basin

understanding of the difficulties of securing Adelaide's water supply and a willingness to pay to have the problem solved. There was also a significant push for increased stormwater re-use, spearheaded by the local government organization that had been successfully re-using stormwater since 1994. In response, the state government commissioned a report into urban stormwater harvesting options for Adelaide (Wallbridge and Gilbert 2009).

In order to provide a formal response to the latest water supply crisis, the state government produced a new water security plan, called Water for Good (South Australian Government 2009), which was launched in the middle of 2009. The new plan adopted a longer-term planning horizon (up to 2050) and was much more "aggressive" in its strategies, both in terms of demand management and additional supply, than the Water Proofing Adelaide Strategy it replaced.

The plan recognized that reliance on Adelaide's traditional sources of water would likely be inadequate into the future, even though this was the cornerstone of the Water Proofing Adelaide Strategy, released only four years prior. The plan advocated a mixture of new supply types, as summarized in Table 3.2. The new 100 GL-per-year desalination plant formed the centerpiece of this strategy, which was to be supplemented much more significantly by stormwater and recycled wastewater than outlined in the Water Proofing Adelaide plan. As can be seen in Table 3.2, the additional stormwater and recycled wastewater sources were to be developed in three stages, with targets by the end of 2014, 2025, and 2050.

In relation to demand management, the Water for Good plan provides additional incentives for ensuring the strategies outlined in Water Proofing Adelaide will be implemented, such as rebates for water-saving appliances, as mentioned above, and outdoor water conservation measures, such as rebates for garden

Table 3.2 Proposed water supply infrastructure for Adelaide (from South Australian Government 2009)

Years	Source	Capacity (ML/year)
2008–2010	Glenelg to Adelaide park lands recycled water project (recycled waste water)	3,800[a]
2009–2010	Southern urban reuse project (recycled waste water and stormwater)	3,800[a,b]
2009–2012	Port Stanvac desalination plant	100,000
2009–2014	Additional stormwater schemes	15,000[a]
2014–2025	Additional stormwater schemes	15,000[a]
2014–2025	Additional wastewater recycling schemes	~22,400[a]
2025–2050	Additional stormwater recycling schemes	25,000[a]
2025–2050	Additional wastewater recycling schemes	25,000[a]

[a] Non-potable supply

[b] This does not supply Adelaide proper, but market gardens in the peri-urban area

mulch. In order to fund the additional water supply infrastructure, changes also were made to the pricing structure, and this is likely to continue, with plans to double the price of water over the next four years. At the time of writing, annual water use charges were $0.97/kL from 0 to 30 kL, $1.88/kL from 30 to 130 kL and $2.26/kL above 130 kL. This compares with $0.44 per kL for the first 125 kL and $1.03 per kL for annual usage above 125 kL in 2005 (the time of writing of Water Proofing Adelaide by the South Australian Government).

Since demand management strategies and water restrictions have been introduced, Adelaide's annual water consumption has been reduced from a peak of around 220 GL in 2001 to approximately160 GL. In terms of daily per-capita water consumption, this corresponds to a reduction from 328 L in June 2003 to 228 L in 2009, which is still relatively high by world standards. In addition, some of the water restrictions were only temporary and were relaxed in November 2009 as a result of good rainfall in the local catchments, which filled the 10 reservoirs in the Adelaide system to near capacity. Overall, the strategies in Water for Good are estimated to result in an annual surplus of capacity over demand of 22 GL in extreme dry years by 2050. This estimate is based on a number of assumptions, such as a 1 in 50 dry-year inflow and a 41 % reduction in catchment yield as a result of climate change.

3.3.3 Future Response (2010 Onwards)

The Water for Good plan maps out Adelaide's water supply future until 2050, although the plan itself recognizes that conditions are likely to change over this time period and is therefore a "living" document that will be reviewed on an annual basis. However, the fact that, like its predecessor, the Water for Good plan does not include stochastic and risk-based performance analyses is of major concern, particularly in light of Adelaide's highly variable hydrologic regime and the uncertainties surrounding climate change predictions. There is also a need to conduct scenario analysis, addressing reduced availability of River Murray water due to factors such as climate change, extreme drought, high levels of salinity as a result of reduced flows, changed operational policies and uncertainties in demand. In addition, there is a need to assess the impact of different climate change scenarios on the availability of the local rainfall-dependent sources of water, considering the outputs from a range of global circulation models.

Given the large number of potential supply and demand management options, coupled with the need to consider multiple, potentially competing objectives (e.g., cost, ecological impact, energy consumption, greenhouse gas emissions, risk-based performance, health impacts, etc.), it would seem prudent to make use of multi-objective optimization approaches in order to identify the strategies that would result in the best possible trade-offs between competing objectives, rather than investing in sub-optimal solutions. However, such considerations do not appear in the plan. There is also no explicit support for ongoing research or engagement with research institutions to ensure that state-of-the-art approaches to the planning and management of Adelaide's water supply system are being implemented. Consequently, it remains to be seen if the lessons of the past have been learned, or whether the management of the system will continue to be reactive, rather than proactive.

3.4 Case Study: Southern Adelaide System

3.4.1 Introduction

In this case study, the performance of the southern portion of the Adelaide water supply system, which is served by the Murray Bridge to Onkaparinga pipeline, as well as the Happy Valley, Mount Bold, and Myponga reservoirs (Fig. 3.2), is assessed at 2050 for different combinations of water supply sources, including inflows from local catchments, water from the River Murray, a desalination plant, rainwater tanks and stormwater re-use. In order to conduct the assessment, the general steps of the systems approach are followed, including definition of objectives, specification of alternative solutions and assessment of the alternative solutions against the specified objectives. Details of the issues considered under each of these headings are summarized in Fig. 3.6 and discussed in detail in subsequent sections. It should be noted that the study conducted here presents a limited number of scenarios for illustration purposes and is subject to a number of assumptions, which need to be tested via extensive sensitivity analyses.

3.4.2 Objectives

In this study, five objectives were considered, covering economic, social/technical and environmental criteria (Fig. 3.6). The economic criterion used was total cost, and greenhouse gas emissions were used as the environmental indicator. Three risk-based performance indicators, namely reliability, vulnerability, and resilience (Hashimoto et al. 1982) were used to measure the social and technical performance

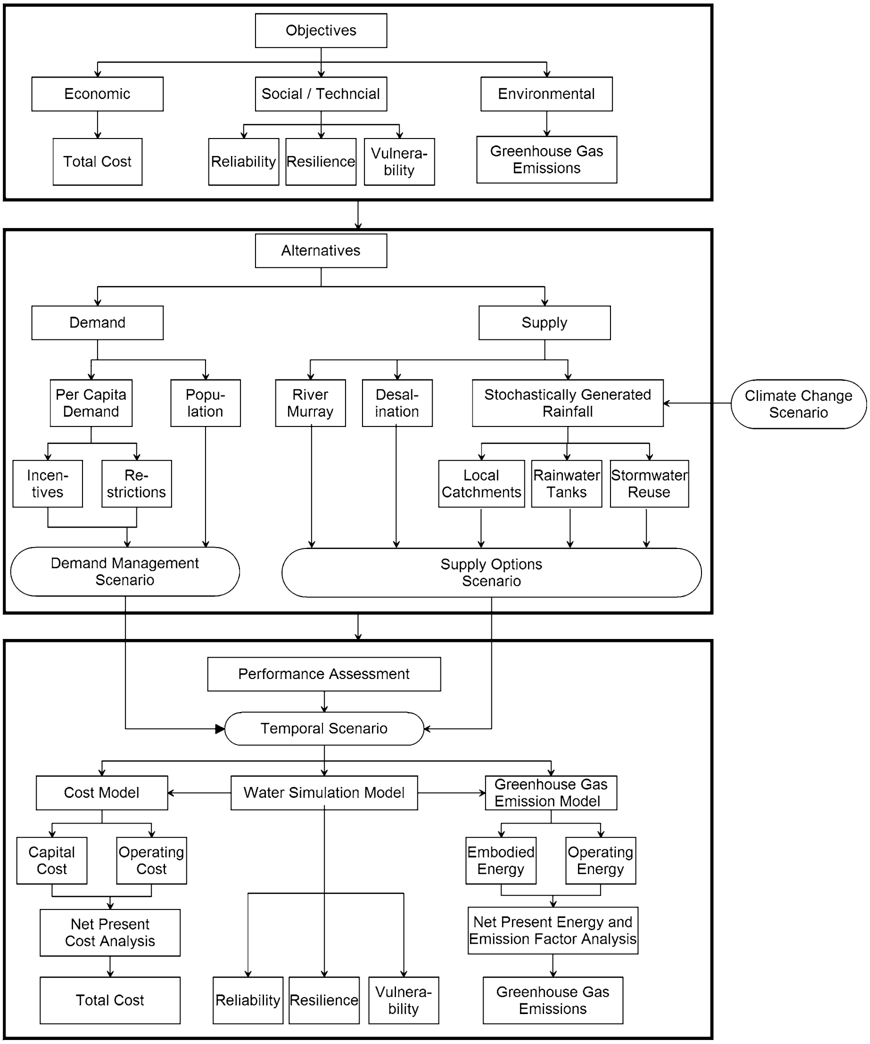

Fig. 3.6 Methodology adopted for assessing the performance of the Southern Adelaide water supply system

of the system. Reliability measures the probability that the system will be in a non-failure state (i.e., the probability that the demand can be met), vulnerability measures the magnitude of the largest failure event (i.e., the largest demand shortfall, in this case) and resilience measures the speed at which the system can recover from failure, as given by the inverse of the average duration of failure (i.e., the inverse of the average length of time demand exceeds supply). Although these measures provide an indication of the technical performance of the system, in this particular instance, they are also strongly linked with social indicators. While it is unlikely that Adelaide will actually run out of water, the actions that will be put in place to prevent this from happening are likely to take the form of water restrictions or other means of demand management, which can have a significant social impact, as discussed previously.

3.4.3 Alternatives

3.4.3.1 Introduction

Alternatives for responding to drought include options for reducing demand and for increasing supply (Fig. 3.6). Demand depends on population, as well as per-capita demand. The latter can be influenced by providing incentives for reducing consumption, such as rebates for adopting water efficient practices (e.g., using water-efficient appliances) or tiered water pricing structures, as well as the imposition of water restrictions. The available supply options are usually case-study dependent. As mentioned previously, in this study, five different supply sources were considered, including the River Murray, desalination, local catchments, rainwater tanks, and stormwater re-use.

3.4.3.2 Demand

A total daily per capita demand of 417 L has been used at the beginning of the time period considered, which is based on an annual per-capita household water demand of 211 kL that has been adjusted for the fact that only 63 % of total demand is residential and the fact that mains water does not account for all of the sources of supply. It should also be noted that the annual per-capita household mains demand use is based on demand during water restrictions, which are likely to be eased once the desalination plant becomes operational. The demand reduction estimates given in Water for Good are incorporated into the analyses by linear (i.e., non-compounded) reductions in annual demand of 0.26 % per annum (pa) for household primary contact water, 0.53 % pa for household secondary contact water, and 0.56 % pa for other uses, such as industry.

The population of the southern system in 2009 was estimated at 590,900 people, which corresponds to 236,360 households. Based on projections from

Water for Good and the Australian Bureau of Statistics, an average population growth rate of 1.2 % pa was used. Consequently, the total assumed demand in the southern system for 2009 was 90 GL, including 30.1 GL/year for indoor primary contact water, 26.6 GL/year for secondary household contact water, and 33.3 GL/year for other demand.

3.4.3.3 Supply

In this study, supply from the River Murray was limited to 32.5 GL/year, which is one quarter of the amount that can be extracted by SA Water from the River Murray on an average annual basis. For the purposes of this study, pumping from the River Murray was assumed to occur once the combined storage in Mount Bold and Happy Valley reservoirs (see Fig. 3.2) was less than 50 %. Supply from the desalination plant to the southern system was limited to 50 GL/year, as it is assumed that the balance of the water produced by the desalination plant will feed the northern system.

The other three water sources are dependent on rainfall in the local catchments. The rainfall data required for the analysis were obtained from the Patched Point Dataset (PPD) (Jeffrey et al. 2001), which is based on observed daily meteorological records from the Bureau of Meteorology that have been enhanced by high-quality, rigorously-tested data infilling and de-accumulation of missing or accumulated rainfall, respectively (Charles et al. 2008). In order to account for spatial variability in rainfall, three representative rainfall stations were selected. The historical data were checked to ensure that they did not exhibit any temporal trends. This was carried out using the TREND software tool (www.toolkit.net.au/trend), which enables statistical testing for trend, change, and randomness in time series data (Chiew and Siriwardena 2005). Next, data from the three sites were used to generate 1,000 stochastic rainfall sequences. This was achieved using the multi-site daily rainfall model contained in the Stochastic Climate Library (SCL) (www.toolkit.net.au/scl), which was developed by the Cooperative Research Centre for Catchment Hydrology (Srikanthan 2005). The 1,000 rainfall time series were then adjusted for climate change using monthly percentage change factors obtained from the CSIRO's OzClim website for the CSIRO Mark 3.5 model. The adjustments were made at five-year intervals, starting in 2010.

Three of the 10 reservoirs that form part of the Adelaide water supply system supply the southern region, namely Mount Bold, Happy Valley, and Myponga. As the Mount Bold and Happy Valley reservoirs are interconnected, they are treated as a single reservoir for the purposes of this study. Runoff in the local catchments was obtained using the WC1 rainfall runoff model, as this was especially designed for the Mount Lofty Ranges (Cresswell et al. 2002). The model was calibrated using data from the 1980s and 1990s and was validated against runoff data for the southern system obtained from Crawley (1990).

Currently, 40 % of Adelaide houses have a rainwater tank connected to their roofs (ABS 2007). However, no reliable information on the volume of the tanks,

Table 3.3 Stormwater systems considered in southern system case study

Stormwater system	Component schemes
West	Port road
	Grange area
South	Mile end drain
	Keswick/Brownhill creek
	Sturt river
Onkaparinga	Field creek
	Christie creek
	Onkaparinga river
	Pedler creek
	Willunga

the use of the tanks or the percentage of roof runoff that is connected to the rainwater tank is available. Therefore, 40 % of households are assumed to have rainwater tanks already, but these are replaced on a step-wise basis at a rate of 1 % per year, based on the assumption that the lifetime of a tank is 40 years. New houses that are built each year as a result of the projected population growth will have rainwater tanks installed. Assumed tank characteristics are that they are made from polyethylene, are round and above-ground. Other assumptions include that a typical roof area is 210 m^2, and that 75 % of the roof area is connected to the tank. In this study, rainwater is assumed to be used for toilet flushing and outdoor garden use only.

Three equivalent major stormwater reuse systems are included in the analysis, each consisting of a number of the smaller schemes, as identified in the report on urban stormwater harvesting options for Adelaide mentioned above (Wallbridge and Gilbert 2009) (Table 3.3). In this study, it was assumed that the impervious area contributing to the stormwater schemes is 350 m^2 per household. This area includes contributions from industrial areas and roads etc. A runoff coefficient of 0.85 was used. In addition, there is a 25 % contribution from the 210 m^2 roof area that is not connected to rainwater tanks. In the scenarios where rainwater tanks were excluded, the additional roof area also contributed to the stormwater schemes, with a runoff coefficient of 0.9.

3.4.4 Performance Assessment

3.4.4.1 Water Simulation Model

A water simulation model is required to determine if and when supply exceeds demand and to check that constraints, such as reservoir levels and pumping limits, are satisfied (Fig. 3.6). The simulation model used was WaterCress (Creswell et al. 2002) because (a) it considers water quality, which is of critical importance when

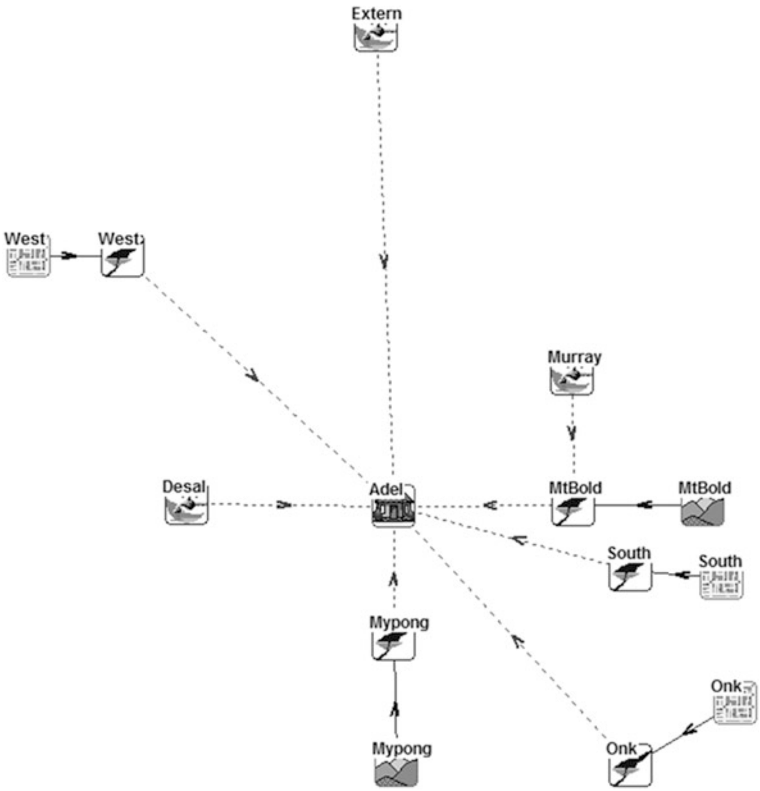

Fig. 3.7 Schematic of simulation model developed for the Southern Adelaide system

comparing different demand types, such as drinking and garden water; (b) it models both the unit scale (e.g., individual demands, internal house supply) and the regional scale (e.g., cities, towns); (c) it can be modified easily for different scenarios; and (d) it can be run for daily time steps over the simulation period.

The WaterCress model developed for this study consisted of a single demand node, which has water supplied internally by the rainwater tank and externally by the desalination plant node, two reservoir nodes (Myponga and combined Happy Valley/Mount Bold), three stormwater system nodes (West, South, and Onkaparinga) and an external source node (Fig. 3.7). The external source node is called on when the other supply nodes cannot meet the demand; so if water has to be used from this source, system failure has occurred. Inflows into the reservoirs are generated using the WC1 model or by pumping from the River Murray (to the combined Happy Valley/Mount Bold reservoir only) and inflows into the stormwater systems are generated from their associated urban catchments, as discussed previously. By running the simulation model over the required time horizon, the number of times supply fails to meet demand, as well as the magnitude and duration of these failure events, can be determined, thus enabling the three risk-based performance criteria reliability, vulnerability, and resilience to be calculated.

3.4.4.2 Cost Model

Cost generally consists of capital and operating costs (Fig. 3.6). As operating costs occur on an ongoing basis, it is common to subject them to net present cost analysis, so that capital and operating costs can be compared on equal footing.

As the reservoirs already exists, there is no associated capital cost. Ongoing costs associated with reservoirs considered in this study include costs associated with water treatment and the costs to replace mechanical assets and the plant. To obtain mechanical asset and plant replacement costs, total plant capital costs were determined, which were then applied every 25 years to simulate replacement of the plant itself. In addition, 16 % of these costs were applied every seven years to simulate replacement of the mechanical assets.

As the infrastructure for transferring water from the River Murray already exists, its capital cost was not included. Ongoing costs associated with the River Murray supply source include pumping and treatment costs.

The capital costs for the desalination plant considered include costs associated with site preparation, construction of the plant and related infrastructure, and the distribution pipeline for the desalinated water. Operating cost estimates used include the costs of pumping, water treatment, chemicals, waste disposal, labor and maintenance. The lifetime of reverse osmosis membranes was taken to be five years and that of the plant, 25 years.

Full costs for the stormwater reuse systems were unable to be obtained, as the only information that was available was that contained in the report on urban stormwater harvesting options for Adelaide commissioned by the South Australian government (Wallbridge and Gilbert 2009). This report did not include costs associated with land acquisition, distribution networks for delivering stormwater to consumers, or operation and maintenance. However, costs associated with transfer pumps and pipe work, bulk earthworks, clay lining, transfer structures within wetlands, aquatic planting, bore establishment and fit out well field pipe work, and mechanical and electrical works required for control of injection were included (Wallbridge and Gilbert 2009).

In relation to harvesting rainwater, capital costs included in the analysis were the costs of tanks, pumps, plumbing, installation, tank base, and tank delivery. Ongoing costs associated with rainwater tanks included pumping and replacement costs. Economic costs were discounted using Gamma discounting (Weitzman 2001), which is a time-declining discount rate.

3.4.4.3 Greenhouse Gas Emission Model

Greenhouse gas (GHG) emissions are a function of energy, both operating and embodied (Fig. 3.6). As operating energy is used on an ongoing basis, it needs to be subjected to net present energy analysis to ensure operating and embodied energy are compared on an equitable basis. In addition, energy has to be converted to greenhouse gas emissions using emission factor analysis, which is a function of the process by which electricity is generated.

As the reservoirs already exist, their embodied energy was not included in the analysis. Ongoing GHG emissions were included for the power required for water treatment and the associated emissions of mechanical asset and plant replacements. However, GHG emissions associated with chemicals and labor were not considered.

The embodied energy associated with transferring water from the River Murray to Mount Bold reservoir was not considered, as this is associated with existing infrastructure. The ongoing energy associated with the River Murray source included pumping costs, as well as some of the ongoing costs associated with storing and treating water at Happy Valley reservoir.

Five percent of the GHG emissions for desalination were attributed to capital costs (i.e., materials and construction), with the remaining 95 % attributed to operating costs (GHD Fichtner and Sydney Water 2005). Due to the large amount of power used in the operation stage, it was assumed that 94 % of the total GHG emissions were attributed to power, and 1 % of the total GHG emissions were attributed to replacing membranes. GHG emissions associated with maintenance and chemicals were unknown and therefore not considered in this study. GHG emissions associated with the construction of the desalination transfer pipeline were based on the embodied energy of ductile iron cement lined (DICL) pipes, the embodied energy of pumps, their associated infrastructure requirements and the energy associated with their installation. The ongoing GHG emissions associated with the transfer of desalinated water were based solely on the CO_2-e emissions from electricity consumption, as it was assumed that the transfer pipeline would not be replaced during the time horizon considered.

The energy associated with the stormwater systems was based on wetland and well construction. As no information was available on stormwater distribution systems, their energy could not be included in the analysis. It should be noted that this omission is likely to have a significant impact on the results obtained and needs to be included in more detailed analyses. Ongoing energy consumption was based on the energy required for pumping water out of the aquifers.

The embodied energy of the rainwater tanks was based on tank material, fabrication process, installation, and maintenance. Ongoing energy was associated with pump operation.

An emission factor of 0.98 kg of CO_2 equivalent (CO_2-e) emissions per kWh was used for converting energy into GHG emissions, as this is the value used for the consumption of purchased electricity by end users in South Australia for the year 2007 (Department of Climate Change 2008). Based on this figure and the fact that 1 MWh is equivalent to 3.6 GJ, the associated emission factor of embodied energy was 272 kg of CO_2-e emissions per GJ.

A discount rate of 1.4 % was used for discounting the impact of future GHG emissions, based on the value used in *The Stern Review on the Economics of Climate Change*. This accounts for the costs and feasibility of abating GHG emissions at around 550 ppm (avoiding catastrophic climate change) over a long-term planning horizon (Weitzman 2007).

3.4.5 Scenarios

As mentioned in Sect. 3.1, only supply option scenarios were considered in this study (Fig. 3.6). Climate change was fixed to IPCC emission scenario B1, which represents a relatively low emission scenario and therefore presents a "best-case" scenario in terms of climate change impact, and demand management options were restricted to the strategies outlined in the Water for Good plan.

In this study, five different supply scenarios were investigated, consisting of different combinations of the supply sources. Supply from the local catchments and the River Murray was considered in every scenario; however, use of the other three sources was varied, including scenarios that included (1) all water sources, (2) all water sources except rainwater tanks, (3) all water sources except stormwater reuse, (4) all water sources except stormwater reuse and rainwater tanks, and (5) all water sources except desalinated water.

3.4.6 Results and Discussion

Values of the performance metrics are given in Table 3.4 for the five different water supply scenarios considered. As can be seen, when all water sources are used, the average reliability of the system over the 1,000 different stochastic rainfall sequences under a B1 climate change scenario is 99.62 %. However, under this scenario, demand exceeds supply very rarely and when shortfalls occur, the average duration is 1.28 years and the maximum deficit is 0.55 GL, which corresponds to 0.51 % of the total demand. Under this scenario, Adelaide's water supply can be considered secure, as the shortfalls can be easily avoided by the imposition of short-term water restrictions.

The scenarios when either stormwater reuse or rainwater tank supply are excluded are very similar in terms of risk-based performance of the system. Overall, the system performs slightly better when the stormwater reuse option is implemented rather than the rainwater tank option. There is a slight increase in reliability and resilience and a reduction in vulnerability by 1.2 GL (Table 3.4). However, this slight increase in system performance is associated with a reduction in cost of $0.54 billion, which is likely to be an overestimate, as not all of the costs

Table 3.4 Southern system performance metrics for 2050 averaged over 1,000 independent runs with different stochastically generated rainfall time series

	Reliability (%)	Resilience (Years^{-1})	Vulnerability (GL)	Present value of cost ($ Billion)	Discounted GHG (Millions of tonnes of CO_2-e)
All Sources	99.62	0.78	0.55	3.89	11.21
No rainwater tanks	98.21	0.71	3.02	3.07	10.54
No stormwater reuse	97.26	0.7	4.22	3.61	11.31
No rainwater tanks or stormwater reuse	89.25	0.6	15.2	2.77	10.48
No desalinated water	0.32	0.02	44.2	1.52	3.24

of the stormwater schemes are accounted for in the analysis, as discussed previously. Although there is a small reduction in GHG emissions for the stormwater option, this is slightly misleading, as operational GHG emissions associated with the stormwater reuse systems are not included in the analysis, as mentioned above.

When neither stormwater reuse nor rainwater tanks are included as water sources, system performance deteriorates markedly, with a reliability of just above 89 %, resilience at 0.6 year^{-1}, which corresponds to an average duration of shortfalls of 1.67 years, and vulnerability just over 15 GL, which corresponds to a shortfall of about 14 % (Table 3.4). Although this scenario saves approximately $0.8 billion, the corresponding system performance is unlikely to be acceptable.

Without the desalination plant, system performance deteriorates drastically, with significant shortfalls for most years. The vulnerability of the system is 44.2 GL, which corresponds to about 41 % of the demand of the southern system. While the no desalination option results in significant cost savings ($2.37 billion) and even greater energy savings ($\sim$8 million tonnes of CO_2-e), it renders the performance of the system unacceptable from a security of supply perspective.

While the results obtained indicated that the risk-based performance of the southern Adelaide water supply system appears to be adequate when all potential water sources are being utilized, this is based on the assumption that half of the average annual allowance from the River Murray is available, which might not be the case under severe drought conditions, particularly when more severe climate change scenarios are considered. In contrast, the projections in the Water for Good plan, which are based on deterministic estimates, rather than stochastic analyses using 1,000 rainfall replicates in conjunction with a daily simulation model (as used in this study), suggest that there will be surplus of 20 GL for the total Adelaide system by 2050 under severe drought conditions. This would equate to an approximate surplus of 10 GL for the southern system. It should be noted that the results obtained in this report are based on limited scenarios and various assumptions. In order to perform a rigorous assessment of the performance of the southern Adelaide water supply system, a large number of scenarios should be evaluated and extensive sensitivity analysis of the assumptions should be conducted. However, the results presented in this study highlight the importance of conducting long-term stochastic analysis and using risk-based performance measures in the planning and performance assessment of highly uncertain and variable systems.

3.4.7 Conclusions from the Case Study

The results of the analysis of the southern Adelaide water supply system indicate that desalination is vital for securing Adelaide's water supply security, if it is to sustain its desired population growth. This is despite the significant financial and environmental burden of this option. The results also indicate that either stormwater reuse or rainwater tanks, or additional desalination plants, are needed to supplement the currently planned desalination plant together with the traditional sources from the local catchments and the River Murray in order to secure Adelaide's water supply.

This study also highlights the benefit of stochastic analysis and risk-based performance assessment when dealing with highly variable and uncertain systems. These approaches should be coupled with extensive scenario and sensitivity analyses in order to provide a rigorous assessment of system performance. The study also demonstrates the need to consider multiple assessment criteria, so that informed decisions can be made about the most appropriate tradeoffs between the various criteria, such as likely water supply security, cost, and greenhouse gas emissions.

3.5 Overall Conclusions

In order to secure Adelaide's water supply, there has been a history of responding to below-average inflows in the local catchments and the Murray-Darling Basin by implementing large infrastructure projects, such as the construction of reservoirs, pipelines and, more recently, a desalination plant. However, in order to secure Adelaide's water supplies in a highly variable and uncertain hydrologic regime, there is a need to be more proactive, rather than reactive. The first steps towards this have been taken through the development of strategic water security plans. However, as illustrated by the failure of the Water Proofing Adelaide plan, the development of longer-term plans is difficult in an uncertain and highly variable environment. The Water for Good plan has attempted to address this by a diversification of management options, both in terms of sources of supply and demand management, as well as provisions for review and adaptation of the plan on an annual basis. However, in order to perform a rigorous assessment of system performance and to plan in a robust and informed fashion, there is also a need to perform stochastic analysis, to use risk-based performance measures and to conduct extensive sensitivity and scenario analysis.

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Chapter 4
Living with Drought in the Irrigated Agriculture of the Ebro Basin (Spain): Structural and Water Management Actions

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Abstract This chapter presents a discussion of a set of technological actions aimed at living with drought in the irrigated agricultural region of the Ebro Basin in Spain. The basin faces recurrent drought episodes that have led farmers to take action on the structural and water management aspects of water conservation. Structural works have taken the form of large irrigation modernization plans, affecting about one-fourth of the currently irrigated land. Modernization typically implies the construction of collective, remote-controlled, pressurized irrigation networks and the installation of on-farm sprinkler/drip irrigation systems. The impacts of these modernization projects on the Ebro Basin hydrology and on the economy and

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productivity of irrigated agriculture are discussed. In parallel, actions have been set up to improve water management, mostly at the water-user association (WUA) level. The cooperative design, elaboration, and dissemination of a database software supporting daily water management operations in WUAs is presented, and the utilities for drought management are discussed. Finally, a plan for action benefiting from improvements on both structures and water management capacities is presented. This new action comprises automated irrigation scheduling and operation, and is based on a combination of remotely controlled networks, WUA management and meteorological databases, and irrigation engineering tools. The proposed action has already undergone significant research and could result in the generalization of scientific irrigation scheduling and in the complete automation of irrigation operation. Technology can support farmers in their efforts to adapt to drought conditions and still obtain sustainable profits.

4.1 Introduction

By the turn of the twentieth century, the government of Spain concluded that the irrigation sector needed to improve its structures and to reduce its water consumption in order to become more competitive and sustainable. At the same time, there was a need to reduce irrigation water use in order to guarantee access to water in the country to all users at all times. In those days, surface irrigation amounted to 59 % of the irrigated area, and 71 % of the area had infrastructure more than 25 years old (MARM 2002). The government of Spain presented a new irrigation policy, the National Irrigation Plan (NIP), promoting the modernization of national irrigation infrastructure (MARM 2002). The plan had two main objectives: (1) to increase the competitiveness of the irrigation sector in order to face the progressive liberalization of agricultural markets and the reduction of subsidies, and (2) to save water (3,000 $\mathrm{Mm}^3\ \mathrm{year}^{-1}$) to alleviate the consequences of cyclical droughts.

Following this policy, irrigation modernization projects have been executed in this decade (2000–2010) on complete Water Users Associations (WUAs). Projects commonly involve replacing surface irrigation systems by pressurized irrigation systems, and constructing on-demand collective, pressurized irrigation networks. The goal was to modernize 2 M ha in a period of 10 years, investing a total of 7,400 M € (Euro). The government created public companies dedicated to managing NIP investments. These companies organize the farmers' requests for modernization, produce project construction documents, manage subsidies to the WUAs, and control the quality and timing of the construction.

Apparently, during NIP execution the total irrigated area in Spain has not suffered significant changes. In 2007, this area could be estimated as 3.48 M ha (MARM 2007). The most relevant change in recent years has been found in the type of irrigation systems, with surface irrigation reducing to 38 % and pressurized irrigation increasing to 62 % of the total irrigated area (MARM 2007). These figures are not representative of the current situation (2010), since the irrigation sector in Spain continues to evolve following the execution of irrigation modernization projects.

The irrigation sector in Spain is exposed to the effects of water scarcity and drought in certain areas. Tió (2000) indicated that 55 % of the irrigated area in Spain had insufficient water allocation. Consequently, the situation is only aggravated by the presence of recurrent droughts. In general, water scarcity is more frequent in the southeastern part of the country, where water resources are more limited in quantity and quality and where irrigation is usually more productive. In a number of Spanish irrigated areas, water scarcity is well documented in the scientific literature. This is the case of Mancha Oriental Aquifer, Murcia or the low Guadalquivir Basin (de Santa Olalla et al. 1999; Custodio 2002). Despite this general trend, drought can appear in any area of Spain, and it often affects WUAs located in the Ebro River Basin, which is the target of this chapter.

The Ebro Basin, located in northeastern Spain, covers 85,566 km^2, about 17 % of the national territory (Fig. 4.1). This is one of the most intensively irrigated basins in Europe (Wriedt et al. 2009), with about 0.80 M ha of irrigated land (24 % of the total Spanish irrigated land). The irrigation systems in the basin show different typologies. The oldest systems were constructed more than two centuries ago (often many centuries ago), are located in riparian areas, and represent traditional, historical irrigation. A second period of irrigation expansion happened between the eighteenth and twentieth centuries (until the 1960s), when large collective irrigation projects, some of them exceeding 0.1 M ha, were developed. Irrigation technology at the time included canals, open ditches and surface irrigation. Since this was the only available irrigation system, the results were not always satisfactory, with significant project areas showing poor irrigation efficiency (Burt et al. 1997; Playán et al. 2000), and some of them being salt-affected (Herrero and Aragüés 1988). The last period of irrigation expansion began in the

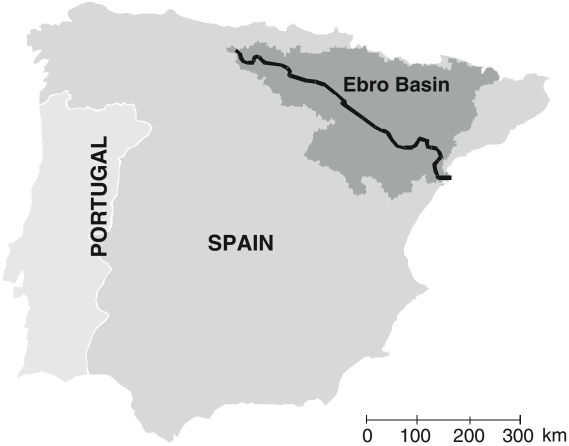


Fig. 4.1 Location of the Ebro Basin within the Iberian peninsula

1970s, with the development of sprinkler/drip irrigation, water pressurization and the widespread use of plastic materials in agriculture. These pressurized irrigation projects require periodical technological updates (some of them are more than 30 years old), but show the general benefits of modern irrigation structures.

Although the Ebro Valley is diverse in its agriculture, its productive orientation is largely based on field crops. Lecina et al. (2008) presented an analysis of the irrigated area dedicated to types of crops, using data from the period 1996–2002. Their results indicate that field crops occupied 58 %, fruit trees 19 %, and olive trees and vineyards 4 % of the total area. Approximately 17 % of the irrigated area was not cropped, due to poor structures, set-aside subsidies and the existence of unproductive salt-affected soils (Herrero and Aragüés 1988; Nogués et al. 2000). The orientation to field crops resulted in 70 % of the area being equipped with low-cost surface irrigation systems just before irrigation modernization plans began (Lecina et al. 2008). This percentage is eleven points higher than the national average. Farmers in the Ebro Basin do not have to live with drought every year, but droughts regularly happen, and require adaptations of a different nature.

In this chapter, technological actions aimed at living with drought in the irrigated agriculture of the Ebro Basin in Spain are discussed. Actions are divided into structural and managerial. The effectiveness of actions addressing irrigation structures and water management is discussed, and the synergic effects resulting from the simultaneous use of both approaches are presented.

4.2 Responses and Adaptations: Past, Present, and Future

4.2.1 The Past: An Era of Intense Water Development

In the past, drought only affected dry-farming agriculture in the Ebro Basin. Irrigation was the final solution for drought, liberating farmers from suffering the economic consequences of crop water stress. These were centuries of water abundance and intense water resources development. Water was always available for new irrigation projects, which were only limited by technical capacity and by the required investments. In the Ebro Basin, water was abstracted from the rivers, constructing large dams and canals. In the twentieth century, the need for hydropower accelerated the construction of reservoirs.

In the last years of the twentieth century, the situation started to change as the construction of irrigation projects progressed (the number of irrigated hectares in the Ebro Basin approached the current figure) and environmental and recreational uses started to count in the water balances. Farmers realized that water was a finite resource. Developing additional water resources became difficult, due to the escalating costs and the social confrontation now accompanying many water resources engineering works.

4.2.2 The Present: Two Separate Approaches

In the irrigation arena, preparing for drought means increasing technical efficiency (irrigation efficiency), with the goal of obtaining the same agricultural yield or income with less irrigation water. According to Allan (1997, 1999) improving technical efficiency would be the last choice, following the use of virtual water and the improvement of economic efficiency. Allan (1999) justified the selection of technical efficiency in that it catalyses other economic sectors (i.e., construction) and does not produce explicit losers. Playán and Mateos (2006) added additional advantages to the improvement of technical efficiency, such as favoring rural development, improving basin-wide water quality, and adding technology to agricultural employments. Two strategies can be followed for improving technical efficiency: improving irrigation structures (irrigation modernization) and improving irrigation management. The following sections describe the actions and analyze the results of both strategies in the Ebro Valley.

4.2.2.1 Irrigation Modernization

This section partially presents the results obtained by Lecina et al. (2008), who elaborated on the hydrological consequences of the current irrigation modernization efforts in the Ebro Basin. The NIP will execute modernization projects affecting 175,000 ha until 2009 (plans for further projects have recently been published). This represents 19 % of the irrigated area in the basin, and 27 % of the surface irrigated area before the NIP. In order to analyze the hydrological changes due to modernization, the first step is to determine water consumption before modernization. This is not a trivial task in Spain, since official statistics are published on water use, not on water consumption. Accounting for water use may be a sensible choice in areas where return flows cannot be reused, but leads to significant conceptual errors in internal basins. This is the case of the Ebro Basin, where irrigation return flows join the Ebro River and may travel for distances exceeding 200 km before reaching the Mediterranean Sea. As a consequence, irrigation return flows can be sequentially reused for a number of economic activities, including irrigation.

Molden (1997) presented a water accounting scheme that can be adapted to irrigation water use. According to these authors, the consumptive part of water use is composed of productive evapotranspiration (crop evapotranspiration), non-productive evapotranspiration (evapotranspiration from phreatophytes and weeds, and evaporation from reservoirs, canals and sprinkler irrigation systems), and non-reusable runoff and percolation (flowing to non-exploitable aquifers or to the sea, or non-reusable waters due to water-quality degradation). These concepts were applied by Lecina et al. (2008) to the Ebro Basin, compiling and analyzing information about crops, crop water requirements, hydrology and productivities. A number of works published by the research group on Irrigation, Agronomy and the

Environment (EEAD-CSIC and CITA-DGA) as well as other authors, were used for this purpose.

Cropping patterns were obtained for the 1995–1996 to 2001–2002 seasons. The results were very different in the areas with surface and pressurized irrigation. In pressurized irrigation, field crops were reduced (from 24 to 4 % in winter crops, and from 44 to 25 % in summer crops); whereas, fruit trees increased from 6 to 30 %, and horticultural crops from 3 to 14 %. Land set-aside decreased in pressurized areas, from 18 to 16 %. The availability of pressurized irrigation resulted in a more intense cropping pattern, since pressurized irrigation increases the productive potential of the soils and reduces the production risks.

Table 4.1 presents the results of a hydrologic and economic analysis of the effects of irrigation modernization in the Ebro valley. Crop water requirements were determined using the standard FAO methods (Allen et al. 1998). An average meteorological year was considered in the study. This analysis reflects that basin wide productive evapotranspiration is expected to increase by 6 % with irrigation modernization (from 2,426 to 2,567 M m^3 $year^{-1}$). A very significant increase (35 %) is expected in the gross value of agricultural production. As a consequence, water productivity expressed as the ratio of the previous variables (Playán and Mateos 2006) will increase by 27 % (from 0.828 to 1.055 € m^{-3}). Under these hypotheses, irrigation productive consumption will increase with irrigation modernization from 17 to 18 % of the average Ebro flow. In terms of the maximum basin storage capacity, modernization will result in a productive consumption increase from 40 to 42 %.

These results were anticipated by Playán and Mateos (2006), who presented three reasons justifying an increase in irrigation productive consumption following modernization. First, an increase in irrigated area without modification of the water rights. Prior to modernization, a number of farms were abandoned due to their poor irrigation structures. After modernization, this land is productive and needs to produce in order to pay back the investment. Second, irrigation modernization increases crop yields due to more uniform irrigation and the possibility of more frequent irrigation (i.e., decreased crop water stress). This increment in yield is generally related to an increase in transpiration. Finally, following modernization, the cropping patterns become more intensive from the points of view of

Table 4.1 Characterization of pre- and post-modernization scenarios in the irrigated land of the Ebro Basin, considering the modernization investments 2002–2009 in the National Irrigation Plan and an average meteorological year. Adapted from Lecina et al. (2008)

	Pre-modernization	Post-modernization
Productive evapotranspiration (M m^3 $year^{-1}$)	2,426	2,567
Gross value of agricultural production (M € $year^{-1}$)	2,009	2,708
Productive evapotranspiration (M m^3 $year^{-1}$ ha^{-1})	2,919	3,089
Gross value of agricultural production (M € $year^{-1}$ ha^{-1})	2,417	3,258
Water productivity (€ m^{-3})	0.828	1.055

economy and hydrology. These results are not in conflict with the expected increase in on-farm irrigation efficiency following irrigation modernization. This increase can lead from a variable and generally poor efficiency in surface irrigation (40–90 %) to a high and uniform efficiency in pressurized irrigation (70–90 %). However, these efficiency figures are not relevant in a water balance established in terms of consumptive water use.

These results make it difficult to attain the water-saving benchmarks established by the NIP. In fact, in the Ebro Basin the situation will only get more complicated, with an increase in consumptive use and a corresponding decrease in river flows to the Mediterranean Sea. Irrigation modernization produces a variety of effects on rural societies and the environment. When effects are considered on the Ebro water balance, irrigation modernization will increase water scarcity in the future, if all other variables remain constant.

The reported increase in consumptive use is not the only consequence of irrigation modernization. Table 4.1 presents two very important additional consequences: the increase in the gross value of agricultural production, and the increase in water productivity. Both are very important to ensure the economic sustainability of modern irrigated areas in the basin. The increase in economic water productivity will promote agricultural water uses among other alternative uses in the basin, and will help to maintain the water-agriculture link in the future. One important social benefit of irrigation modernization is the conservation of the irrigated land in the rural areas. Possibly many old traditional surface-irrigated fields could be abandoned in the near future without the modernization process.

An additional benefit of irrigation modernization is related to the expected decrease in pollutant loads in irrigation return flows. Lecina et al. (2009) analyzed this effect, and concluded that the improvement in on-farm irrigation efficiency and the decrease in conveyance losses will result in a very important decrease in irrigation runoff and percolation losses. As a consequence, soil leaching will be reduced, and the mass of exported fertilizers and other salts will decrease. The generalized adoption of fertigation in pressurized irrigation will lead to a better control of fertilizer application and to a further decrease in fertilizer use. As a consequence, irrigation modernization will contribute to reach the objectives of the European Water Framework Directive (European Union 2000), which requires water bodies to reach a “good ecological status” by 2015. Irrigation modernization will decrease the load of salts and fertilizers in the irrigation return flows, and the volume of return flows. At very specific points of the river system (within or near the irrigated area), this will lead to an increase in pollutant concentrations, negatively affecting the direct reuse of these waters for urban, industrial, and agricultural uses. In general, the effect of modernization on water quality will be very positive.

Finally, the modernization of the irrigation systems produces an important effect on rural societies, increasing the technical profile of rural jobs. Farmers and WUA employees will need to increase their labor skills to deal with the elements of pressurized networks and to be able to enjoy the benefits of irrigation controllers and remote surveillance and control systems. Additionally, farmers with pressurized systems will start to use the information on crop water requirements to optimize the irrigation depth. These technologies are an incentive for young professionals to engage in activities that in recent decades were in the hands of aged persons.

The analysis of irrigation modernization has led to positive and negative aspects. The most negative aspect is that modernization will not alleviate pressure on the river. In contrast, water scarcity will increase, and the basin will be one step closer to “closure” (no additional consumptive water uses are possible in the basin) (Seckler et al. 2003). As a consequence, drought will appear more frequently on the basin, although this effect will have a small quantitative importance (the increase in evapotranspiration was estimated as 6 % in the future scenario).

The most significant effect of modernization on drought will be appreciated at the upper parts of the basin. In these areas, irrigation supply directly depends on reservoirs, and there is no physical chance of diverting return flows for irrigation from upstream WUAs. The improvement in irrigation efficiency will be very important in these areas, since the volume of water stored at the reservoir is divided among the irrigated area, and farmers need to make the most of this volume. Playán et al. (2000) presented an analysis of the Almudévar WUA, which is located at the *Riegos del Alto Aragón* irrigation project. Before modernization, this area had an average application efficiency (Burt et al. 1997) of 54 %, implying that in order to apply the readily soil available water, estimated as 70 mm, a total of 130 mm had to be applied to the soil. In particular areas of the WUA, application of more than 200 mm was required to store as little as 40 mm in the soil (application efficiency of 20 %). In other areas of the WUA, however, surface irrigation attained efficiencies beyond 80 %, and less than 125 mm was required to apply 100 mm to the soil. This large spatial variability is very typical of surface-irrigated areas. The abovementioned gross irrigation depths in surface irrigation cannot be reduced, since they are required for the irrigation water to advance to the end of the field. The situation can be even more complicated in other WUAs in the basin, where drought-induced restrictions are passed to farmers as a reduction in both allocated water volume and irrigation discharge. Reducing discharge implies an additional problem in surface-irrigated areas, since it results in a further decrease in application efficiency (Playán and Martínez-Cob 1999). In 2010, the Almudévar WUA will start operation, following irrigation modernization. Application efficiency will likely be as high as 80–90 %, and the irrigation depth will be fixed by the farmers with no minimum requirement.

Summarizing this section, irrigation modernization will lead to improved river water quality, due to decreased pollutant loads in irrigation return flows, but will not produce net water saving in the basin. Moreover, it will add to the factors leading to basin closure, and it will increase the frequency of droughts. Modernization will increase crop evapotranspiration and, therefore, aggravate the effects of meteorological droughts. However, the improvement of irrigation efficiency following modernization will result in a clear opportunity to sustain agricultural production in some WUAs during drought periods.

4.2.2.2 Irrigation Management: The Ador Software

The efforts to improve irrigation management in the Ebro Basin have so far run in parallel to the structural actions. Water management has received limited attention on the part of public administration, although it requires very moderate investments, as compared to structural actions. As a consequence, irrigation management can be more effective in terms of water conservation and drought management than irrigation modernization. There are two additional advantages to irrigation management that are significant in this discussion. First, the improvement in irrigation management is a bottom-up approach: it is generated at the lowest level of water management, and it impregnates all decision-making levels as it proceeds to the organizational top. Second, it produces institutional strengthening at the WUA level. The role of the WUA personnel gains in relevance as they improve their management level and they use better information.

Several authors have stressed the importance of improving the service quality of WUAs. Clemmens and Freeman (1987) reported that WUAs influence the performance of an irrigation project, noting the relevance of a bidirectional information flow between the WUA and its farmers. A few research efforts have been reported in the past on WUA databases (Merkley 1999; Sagardoy et al. 1999; Mateos et al. 2002). In the following paragraphs, a software for WUA management will be presented, focusing on the utilities for irrigation water control under drought periods. The software is named Ador, and the principal design criterion was to enforce adaptability to the different types of irrigation water management performed in the traditional and modern WUAs in Spain. The application of the software to the specific case of the *Riegos del Alto Aragón* irrigation project will be discussed.

The Ador software was presented by Playán et al. (2007) as a contribution to the daily management of WUAs. Software development began in 1998, with the Irrigation, Agronomy and the Environment research group (EEAD-CSIC and CITA-DGA) obtaining research grants from the National Research and Development Plan of the government of Spain and the FEDER funds of the European Union. Software implementation enjoyed additional funds from WUAs, particularly within the *Riegos del Alto Aragón* project, and the government of Aragón. The irrigation extension office of the government of Aragón (Oficina del Regante) committed funds to software development and implementation, which started in 2001. A number of consulting and engineering firms contributed to these activities. Recently, Ador version 2.0 has been released, co-sponsored by a public company of the government of Aragón.

Ador has three components: a comprehensive database structure, a diagram of the water distribution network, and a GIS module. Technically, Ador is a Microsoft Access$^{\mathrm{TM}}$ application composed of 118 interconnected tables. Ador is being developed in the Spanish language. The last software version, along with the users' manual produced by the *Oficina del Regante* can be freely downloaded from http://www.eead.csic.es/ador.

A water user is any person or company playing a role in the WUA. This role may be classified in any water use category, such as agricultural, animal farming, industrial, and urban. A water user can be a landowner, a grower or an enterprise. Water users perform their activities in cadastral plots. Each plot is identified by a unique alphanumeric code. Farms are often divided into several cadastral plots. A cadastral plot can be the physical basis of several water uses of different categories (two crops, one animal farm, an alfalfa processing factory, and the farmer's residence).

The irrigation distribution and drainage networks are addressed using a diagram that the WUA manager can modify and extend. Primary network elements include canals, pipes, reservoirs, pumping stations, and water meters. Longitudinal primary elements (pipelines and open channels) can contain secondary elements (hydrants, checks, siphons, valves, air-release devices, and manometers). Figure 4.2 presents part of the diagram of a WUA using both open-channel and pressurized elements. Each water use is related to two users: (1) the user paying for water; and (2) the user paying the fixed costs. For each agricultural water use, the database can store the crop grown and a detailed description of the on-farm irrigation system. Figure 4.3 describes the linking of primary elements, hydrants, cadastral plots, and water uses.

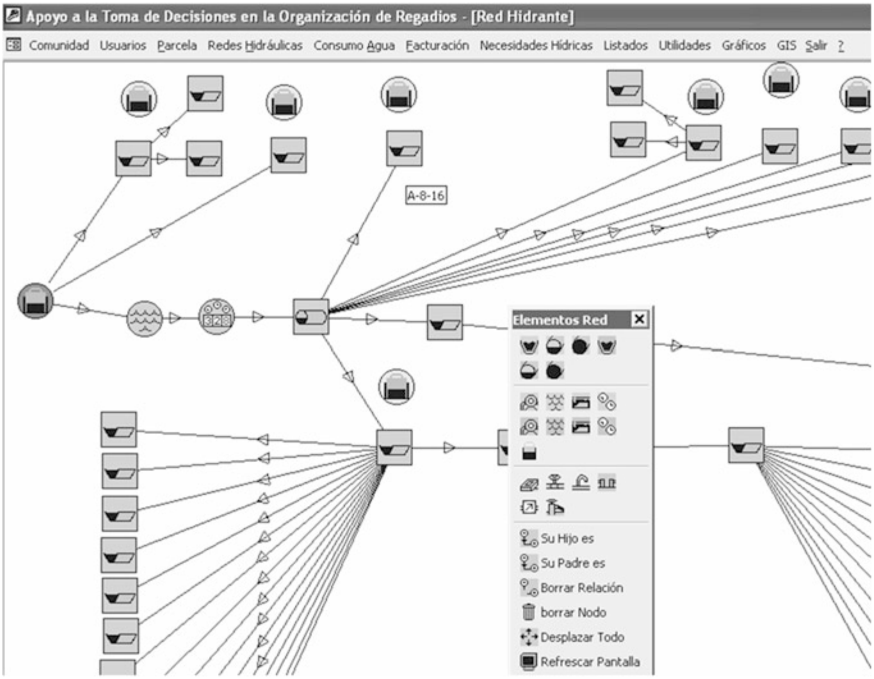
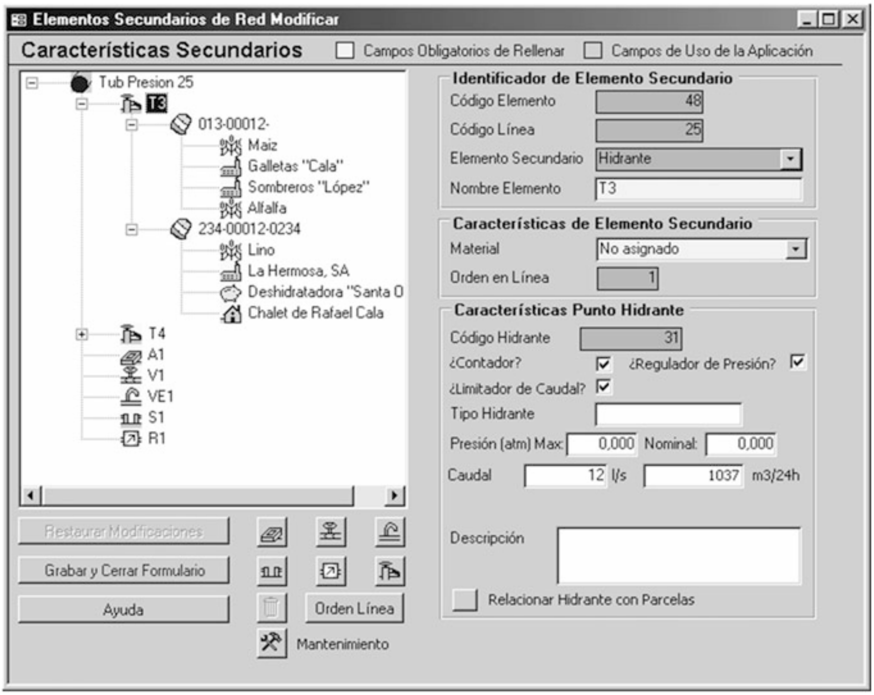


Fig. 4.2 Diagram of the primary elements of an irrigation network in the Ador software. Water flows from the icon representing the water source diversion to a branching canal network. The figure also presents the toolbox used to build and manage the diagram



☐ Campos Obligatorios de Rellenar ☐ Campos de Uso de la Aplicación

Identificador de Elemento Secundario

Código Elemento: 48

Código Línea: 25

Elemento Secundario: Hidrante

Nombre Elemento: T3

Características de Elemento Secundario

Material: No asignado

Orden en Línea: 1

Características Punto Hidrante

Código Hidrante: 31

¿Contador? ☑ ¿Regulador de Presión? ☑

¿Limitador de Caudal? ☑

Tipo Hidrante:

Presión (atm) Max: 0,000 Nominal: 0,000

Caudal: 12 l/s 1037 m3/24h

Descripción:

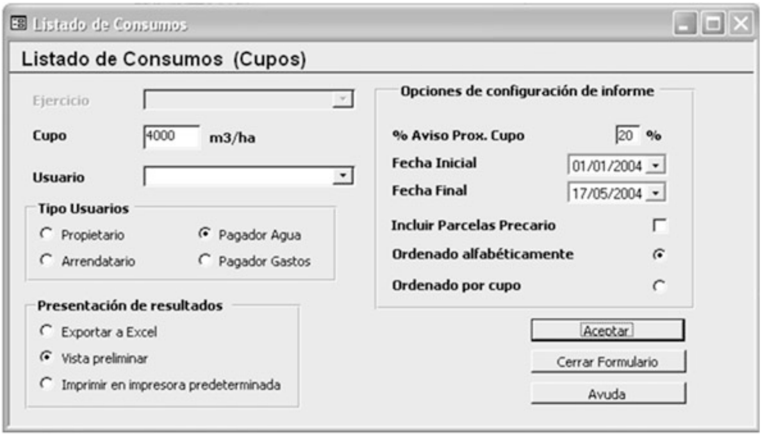
☐ Relacionar Hidrante con Parcelas

Fig. 4.3 Example of the detail offered by the diagram about a primary element of the irrigation water distribution network in the Ador software

Water distribution can be performed in a WUA following a number of different delivery schedules (Clemmens 1987; Clemmens and Freeman 1987). Ador has been designed to accommodate the delivery schedules typical in the Ebro Basin: on-demand irrigation with volumetric water meters; arranged irrigation, based on prepaid water; arranged irrigation, based on previous water orders; and rotation irrigation. Water prices are described in Ador using a two-dimensional matrix, including the type of water and the category of water use. Different water types can be established in a WUA to reflect differences in water quality, origin, or energy input. Fixed and variable costs are considered separately during the billing process.

Many WUA managers consider the water bill as the main goal and the end of their activity. In Ador, the bill is the starting point to promote the improvement of irrigation water management. This is possible if the bill provides additional information. The Ador water bill informs the farmer of his individual water use, but also includes statistics about water consumption in the WUA. The contrast between water use in a certain plot, crop water requirements, and the average water use in the WUA by crop, irrigation system, and soil type helps the farmer to evaluate his level of irrigation water management.

Geographic Information System (GIS) coverages of the cadastral plots and irrigation network can be used to display the database cartographically. WUAs



Listado de Consumos (Cupos)

Ejercicio

Cupo 4000 m3/ha

Usuario

Tipo Usuarios
○ Propietario ● Pagador Agua
○ Arrendatario ○ Pagador Gastos

Presentación de resultados
○ Exportar a Excel
● Vista preliminar
○ Imprimir en impresora predeterminada

Opciones de configuración de informe
% Aviso Prox. Cupo 20 %
Fecha Inicial 01/01/2004
Fecha Final 17/05/2004
Incluir Parcelas Precario ☐
Ordenado alfabéticamente ●
Ordenado por cupo ○

Fig. 4.4 Ador dialogue box for the establishment of a limitation of 4,000 m^3 ha^{-1} following a drought event. A report is produced indicating the users who have reached the limitation, the users within 20 % of the limitation and the rest of the users

must adapt the official GIS cadastral coverages by selecting plots belonging to the WUA, and must produce an irrigation network coverage.

Measures can be adopted in Ador to manage scarce water during drought periods. The software incorporates a tool to establish water demand limitations fixed at a certain allocation threshold expressed in units of m^3 ha^{-1}. A report is produced listing agricultural water users and their current level of water use. The report is ordered by water use, separating the users exceeding the allocation threshold, those who are close to the threshold and, finally, those who have used a limited amount of water. The report is then used to guide further water allocation in the WUA. Figure 4.4 presents the dialog box used to establish water demand limitations.

Ador is currently being used in some 70 WUAs, accounting for more than 175,000 ha in the central Ebro Valley. These WUAs cover a wide range of irrigation technologies and water delivery schedules. Software dissemination started at the *Riegos del Alto Aragón* Project, which includes 53 WUAs and 124,000 ha in the provinces of Huesca and Zaragoza. The project also supplies urban water to more than 100,000 persons, and to several industrial factories and animal farms. In 2001, this project decided to make Ador its standard water management software, with the following objectives: (1) To implement Ador progressively in their WUAs; and (2) to develop a specific data centralization unit at the main project office. Since its onset, the project has been managed by a multidisciplinary steering board. The discussions held in the steering board, and the bi-directional communication with WUA managers have made Ador a widely participative project.

In recent years drought has been a common trait in the Ebro Valley, and it has severely affected *Riegos del Alto Aragón* (among other irrigation projects). Farmers in this project specializing in field crops have seen water allocation restricted in a number of recent years. Due to strong restrictions, farmers have had to concentrate the available water on part of their farming land. This situation has been particularly difficult in areas characterized by low application efficiency. In other years, prospects have been quite hard at the beginning of the season, but later periods of precipitation have resulted in eased restrictions along the season. In this surface water project, restrictions are very variable in time.

The irrigation project's steering board decides the seasonal volume of water allocation in their meetings. Every time a modification in water allocation is agreed upon, all WUAs need to adapt to the new situation. In practice, this means obtaining a new report using the dialog box in Fig. 4.4. These reports are published and communicated to farmers, who can then modify their cropping and irrigation plans accordingly.

A number of farmers' strategies have been identified in these water-restricted years. Some farmers have decided to plant all their land to barley, an early harvesting, low-water use, and drought-resistant crop. In the worst-case scenario, barley can be harvested in June, and that puts an end to the season. If the situation improves during spring, a second crop of corn or sunflower can be established. This double-cropping scheme is greatly favored by irrigation modernization (sprinkler irrigation) and by direct-sowing machines. These technologies are required to quickly plant the second crop and, therefore, take advantage of the warm, sunny July days. Other farmers grow alfalfa with the intention of applying irrigation depths lower than required. Alfalfa shows a linear relationship between irrigation and yield. Being a multi-annual crop, alfalfa has the additional advantage that it survives severe droughts.

4.2.3 Modernization and Management: Exploiting Synergies

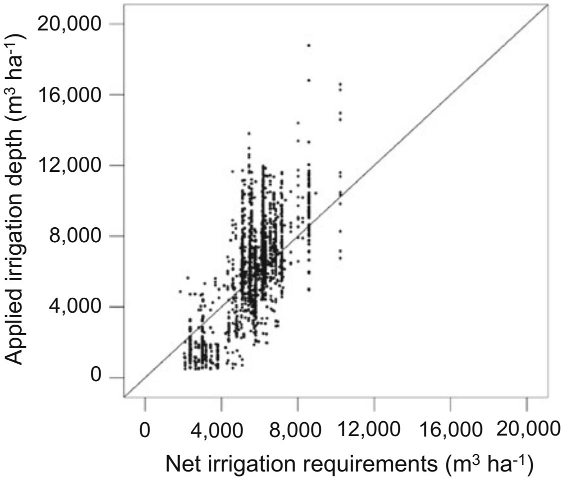
The differences in irrigation technology have resulted in very different farm approaches to drought. Surface-irrigation farmers using border or basin irrigation in *Riegos del Alto Aragón* often need between 1,000 and 2,000 m^3 ha^{-1} to complete the first irrigation of the season, since this first irrigation is usually made in a recently plowed field and therefore high infiltration and low water advance occur. In a drought season, this volume of water represents a significant part of the seasonal allocation (from 3,000 to 5,000 m^3 ha^{-1}). As a consequence, these surface irrigation farmers usually plant barley or wheat, if drought can be anticipated at sowing time. Sprinkler irrigation farmers are free to decide the irrigation depth, and can adapt better to drought situations and to changes in meteorology. This flexibility that characterizes modern irrigation systems is very important to protect farm income in drought years. Synergic effects can be exploited by farmers making use of modern irrigation structures and elaborate water-management procedures.

4.3 The Future: Water Management

In the previous section, several important advantages of water management have been highlighted, relating to cost effectiveness and institutional growth. Unfortunately, there is an important limitation to water management: it relies on the human factor, and its implementation progresses at the speed of change in human resources. Human resource processes are typically much slower than irrigation modernization. As a consequence, it is easy to foresee that by the time irrigation modernization has made a significant progress in the Ebro Basin, irrigation management will still require significant attention from the individual farmers to the boards governing irrigation projects. This is why in the decades to come, efforts will have to focus on water management.

Water restrictions will continue or increase in the future, incremented by irrigation modernization and fostered by competitive water uses, including environmental and recreational uses. As a consequence, in order to maintain a level of economic performance under drought conditions, farmers will need to better adjust water applications to crop water requirements. At present, significant possibilities for improving irrigation performance can be observed. As an example, Fig. 4.5 presents a scatter plot of net seasonal irrigation requirements vs. irrigation water application in agricultural fields throughout the Ebro Basin. These observations were compiled by Martínez-Cob et al. (2005), and contain data from different locations in the basin, a wide variety of crops and all types of irrigation technologies. These data confirm that there is a very large variability in the way farmers respond to crop water requirements. This variability does not only depend on the farmer, since it is very often related to the managerial rules characterizing the WUA. For cases in which irrigation application is lower than crop water

Fig. 4.5 Scatter plot of seasonal net irrigation requirements versus irrigation depth application in the Ebro basin. Adapted from Martínez-Cob et al. (2005)



requirements, structural water scarcity, drought events or regulated deficit irrigation can be relevant factors determining farmers' behavior.

As modern irrigation structures are installed, and on-demand irrigation is made possible, farmers will become more and more responsible for irrigation decision making. Training farmers and WUA personnel in water management skills will become very important to overcome drought periods. The information provided by the Ador software can provide farmers with valuable feedback on how to improve water use in their crops.

A parallel approach consists of the automation of irrigation scheduling and execution, a technique that is now technically possible since:

1. A network of automated agro meteorological stations has been installed in all the irrigated areas of Spain. The SIAR network, installed by the government of Spain in cooperation with the regional governments, publishes daily crop water requirements for hundreds of stations on the Internet.
2. Irrigation modernization projects include a remote-control/supervision module. This module permits operation of all the valves in a collective pressurized network from a central computer.
3. WUA management databases—such as Ador—are now installed in most WUAs. These databases contain information on farmers, plots, crops, structures and irrigation events.

The connection of these three elements permits to a vision in the near future in which a computer determines crop water requirements and applies them to the different farms via the remote control system. Zapata et al. (2009) presented successful simulation results of the application of such a system in a WUA belonging to the *Riegos del Alto Aragón* project.

During the 2009 irrigation season, an experiment was performed at the EEAD-CSIC experimental farm, in which an automatic scheduling system was applied to the irrigation of a corn crop following a statistical experimental design. The experiment compared two irrigation treatments: a farmer following the weekly information produced by the SIAR network, and the automatic scheduling system. Corn yield was statistically indistinguishable, with yields of 16,262 and 15,645 kg ha^{-1} for the farmer and automatic treatments, respectively. While the farmer applied 8,623 m^3 ha^{-1}, the automatic system applied 7,036 m^3 ha^{-1}. This experiment proves that automatic scheduling can result in water management as good as, or better than, the best farmer. This is very important at a time when many farmers are part-timers, and when best management practices are required to overcome drought periods. A centralized water management scheme must combine intelligent on-farm decision making with optimum management and flexible operation at the WUA, so that farmers can easily introduce their priorities in irrigation scheduling. The water management expertise contained in the current crop water simulation models, such as in the recently released AquaCrop (Steduto et al. 2009), can be very useful to these centralized systems in order to optimize water application under drought.

4.4 Conclusions and Recommendations

The irrigation modernization projects currently under development in the Ebro Basin will result in social, economic, and environmental advantages. When it comes to evaluating the effect on watershed hydrology, it seems clear that evapotranspiration will increase if the rest of the variables remain constant. This is an important point, since an in-depth analysis of the effects of irrigation modernization should include aspects such as: (1) the sustainability of the traditional WUAs not involved in modernization projects; (2) the acreage of new sprinkler irrigation systems; (3) the future prices for crops, water and energy; (4) the economic and population growth. If basin evapotranspiration increases, modernization will contribute to water scarcity and watershed closure, and drought events will increase their frequency and intensity. Irrigation modernization will however contribute to drought management at farm scale, particularly at the upper areas of the basin where water is provided directly from reservoirs. Improving application efficiency will help to protect farm income under severe water restrictions. The benefit/cost ratio will always be lower for irrigation modernization projects than for irrigation management. The advantages of cooperative programs for management improvement go well beyond irrigation efficiency, and include endogenous, participative, and multidisciplinary progress. The case of the Ador software, with a history of more than 10 years of co-evolution between water users, water managers, researchers and consultants, illustrates this process. The transparency that Ador has introduced in water management activities has permitted conflict-free operation during drought years. The future will bring more activities in the field of management, and less structural changes. Further research will be needed to develop management tools that take advantage of the different technologies currently available for irrigation operation. Among them, the complete automation of irrigation scheduling and operation stands as a promising line of work. The irrigation modernization projects in place in Spain have required very heavy investments on the part of the farmers and the government. Today, the cost of a typical irrigation modernization project is similar to the price of the land. Such investments cannot be performed in many agricultural areas of the world. As a consequence, irrigation modernization will in many places be a step-by-step process that will have to wait for higher prices of agricultural commodities. In contrast, the prospects for the generalization of efforts in irrigation management are much better, since the costs are orders of magnitude lower.

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Chapter 5
Irrigation and Drought in a Southern Australian Climate that is Arid, Variable, and Changing

Peter Hayman and Michael McCarthy

Abstract This chapter attempts to shed light on the recent crisis by briefly examining how irrigation and climate have been thought about in Australia in the past and how this is likely to change in the future. The focus is the irrigation block and vineyard level of the South Australian Riverland. The chapter summarizes opportunities and limits to adaptation options, including further gains in efficiency, closer monitoring of water requirements, and the use of weather and climate forecasts. We conclude by observing the complexity of thinking about drought in a climate that is arid, variable, and changing. Irrigation in Australia was designed to turn arid regions into an oasis. A century later, drought has forced a major and unplanned restructure. Many irrigators hope that it is just a drought, some worry that rather than a cyclical drought, we are seeing manifestation of a drying, and that the real worry is an increasing aridity.

5.1 Introduction

The drought that developed over the last decade in southern Australia has been referred to as the first irrigation drought. Although a slightly simplistic view of history, it is certainly the case that, until recently, media attention, policy and science have focused on the link between drought, dryland farming, and grazing. Irrigators, especially those growing high-value perennial horticultural crops using high-security water rights, were seen as drought proof because, prior to this drought, water had always been made available.

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In the early twentieth century, irrigation development in Australia was primarily seen as a means of dealing with aridity rather than intermittent droughts, a process of making the desert bloom. There was abundant land, seemingly appropriate soils, solar radiation and temperature were not limiting; a case of simply add water. Water was cheap because the costs of infrastructure were borne by government, while infrastructure maintenance costs and salinity were in the distant future. In the latter part of the twentieth century, emphasis shifted from a pioneering view to productivity as measured by the amount of yield and returns per ML of water. Efficiencies were sought in the application of irrigated water (e.g., drip irrigation and land leveling) and the timing of irrigation (irrigation scheduling). The beginning of the twenty-first century has been a time of increasing recognition of the vulnerability of irrigation in the Murray Darling Basin. The recent drought and emerging problems of rootzone salinity have highlighted what ecologists have long known about the tradeoffs between efficiency of a system and its resilience.

This chapter focuses on irrigation practices within the farm gate and how irrigators, especially in the South Australian Riverland, have used irrigation as a means of dealing with Australia's variable and changing climate. The Riverland region is an irrigated horticultural production region extending for 330 km along the River Murray, between the border of South Australia and Victoria, and Blanchetown in South Australia. The region has an elevation of between 50 and 150 m above sea level and is considered to be a warm climate, wine-growing region that is characterized by long, hot dry days with cool nights. Annual rainfall is about 200 mm, and potential evaporation is 1,900 mm. The Riverland is the largest wine grape producing region in Australia, accounting for 61 % of South Australian wine grape production and 28 % of national production. Water requirements for wine grape production in the Riverland region are met almost exclusively by irrigation from the River Murray. Irrigation water in the Riverland is commonly between 0.4 and 0.6 dS/m (WHO drinking water standards are 0.8 dS/m). These levels require careful irrigation management to avoid build up of damaging levels of salt in the root-zone and grapevine.

The South Australian Riverland is in the northern half of the South Australian (SA) Murray Darling Basin. It is located at the downstream end of an over-allocated river system but upstream of the highly stressed lower lakes. The Riverland has a higher portion of pressurized irrigation systems, compared to most other irrigation areas in the Murray Darling Basin (Fig. 5.1). Meyer WS (2005) noted that due to the interaction of geology, soils, topography, value of crop, and irrigation methods, the New South Wales (NSW) Murray region used 2,000 GL to irrigate (primarily flood irrigation) 321,000 ha and produce a farm gate revenue of about $310 million. In contrast, the SA Riverland used 311 GL to irrigate (primarily micro sprinkler and drip) 36,000 ha and produced a farm gate revenue of $555 million. Using prices from 2005, the Riverland produced almost twice the revenue with one-sixth of the water and one-tenth of the land.

Most Riverland growers at the beginning of the decade would have been aware that along with the strengths of their irrigation region, there were significant water

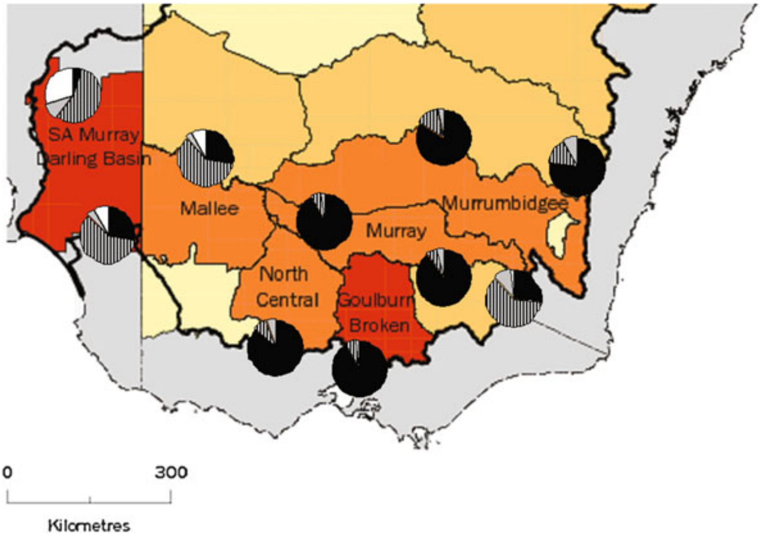

Fig. 5.1 Map of southern half of Murray Darling Basin showing Natural Resource Management (*NRM*) regions and proportion of irrigation application methods for irrigation districts as pie charts. The color of each NRM region indicates the number of irrigation farms in 2005. More than 2,000 (*red*), between 1,000 and 2,000 (*orange*), between 200 and 1,000 (*brown*) and 1–200 (*yellow*). The *pie charts* represent the distribution of application techniques by area for; flood (*black*), sprinklers (*striped*), micro sprays (*grey*) and drip (*white*). Each *pie chart* is associated with an irrigation district. From *left* to *right* on the map the districts are Riverland, Lower Murray, Sunraysia, Loddon Campaspe, Goulburn Broken, Coleambally, NSW Murray, Murrumbidgee, Upper Murray and Upper Murrumbidgee. Source of map of NRM regions and number of irrigation farms (Australian Bureau of Statistics 2008). *Pie charts* of regional distribution of water redrawn from Meyer WS (2005)

quality issues. This was, in part, because salt progressively accumulates downstream, and the local geology of the Riverland leads to significant additions of salt. It is unlikely that drought would have been high on their list of concerns. In the El Nino of 2002, large areas of Australia were in drought. However, because the region had access to high-security water, drought was a concern for neighboring dryland farmers and climate change a concern for polar bears. In addition to access to high-security water and knowledge that storage levels were reasonably high, wine-grape growing was profitable. Yields of 25–30 t/ha and sometimes up to 40 t/ha of chardonnay at $700–$900/tonne were typical. As discussed in the next section, the region suffered the double shock of low-water allocations and an offer for chardonnay in December 2009 of $110 per tonne when growing costs were nearly $300 per tonne.

5.2 The Crisis for Riverland Irrigators

As other authors from the Australian case study in this volume have pointed out, the drought that has developed over the last decade in Southern Australia has been a crisis that has led to changes in policy at national and state levels, and changes in behavior at urban household and irrigated farm levels (Kendall 2013; Connor and Kazcan 2013). Along with catastrophic impacts on wetlands and flood plains throughout the Murray Darling basin, the impact on owners of orchards and vineyards that have been abandoned has captured national and international media.

An example of media attention at the state level in South Australia is an article in November 2009. The *Adelaide Sunday Mail* reported that South Australia's irrigated food bowl was in crisis. "More than a third of SA's River Murray food bowl is vacant as grinding drought, low commodity prices, a high Australian dollar, cheap imports, and a wine glut force irrigators to cut back on plantings or simply walk off the land." The article, with stark pictures of abandoned orchards and vineyards described an "exodus," whereby over the last decade, the number of citrus growers had halved from 926 to 481. About 250 or 10 % of small-block irrigators had applied to the federal government for the offer of $150,000 to leave the land. Regional leaders were reported in the article as estimating that 30 % of the water allocated to the region would be sold to other regions or purchased by the government for environmental flows, and 15 % of farmers would leave the region. The local Member of Parliament and Minister for the River Murray, Karlene Maywald, described the situation as a "collision of calamities" (*Sunday Mail* 2009).

A number of observations can be made from this article that serve as background to this chapter.

- The article highlights the spectrum of risk. For irrigators, the crisis is not just about water shortage. Two notable risks are price risk, due in part to a global downturn having a significant impact on discretionary expenditure on fruit and wine grapes, and a direct relationship between price risk and currency risk due to the exchange rate where goods are sold on a world market. A major risk is policy risk, whereby the rules regarding their water allocation and the ability to trade water are uncertain. Although costs fluctuate within a relatively small range, in 2008 there was a dramatic spike in the cost of agricultural inputs, especially fertilizer costs. Although interest rates have stayed relatively low, there has been substantial business risk, whereby irrigators are at a vulnerable end of a supply chain that is being driven by supermarkets and large wine companies that have been in a major state of flux. As discussed in more detail later, even though the emphasis of climate risk is on water supply, the region had been affected by frost in October 2007 and heat waves in February 2004, March 2008, and late January-early February 2009. Irrigators will be quick to point out that the drought and water supply is one source of risk and only part of the crisis. If commodity prices were high, irrigators could afford to buy more water for their crops.

- It is noteworthy that for urban readers of this article in 2009, no explanation is required to associate drought with irrigation. As recently as the widespread drought of 2002, the phrase a "grinding drought" would be more commonly associated with dryland farmers looking at a failed crop or starving stock. If there was a reference to a dam, it would be a small farm dam that had dried up. The productivity commission (2009) made reference to the first irrigation drought. In their submission to the Parliamentary Enquiry, the industry body representing horticulture (Horticulture Australia Council 2008) noted that horticultural growers *"were struggling for the first time ever with insufficient water to produce a crop"* They described the deepening crisis for the lower Murray Darling Basin as an "unprecedented process of unplanned structural adjustments on a massive scale…with consequences for growers, farming families, local businesses and regional communities." A feature of the first decade of the twenty-first century was that irrigated farmers were seen to be vulnerable to drought rather than drought-proofed. Large reservoirs at very low levels became one of the most common images of drought. It is common to distinguish between meteorological drought (departure of rainfall from long-term average), agricultural drought (soil water deficit leading to reduced crop and pasture growth), and hydrological drought (impact of rainfall shortage on surface and groundwater supplies) (American Meteorological Society 2000). One of the key differences between these types of drought relates to memory in the system; the atmosphere has limited memory, whereas, hydrology has long lag times associated with longer memory. A hydrological system like the Murray Darling Basin with a high storage-to-flow ratio has substantial memory, hence, it will be slower and less likely for irrigators to experience drought. However, once they do experience drought, recovery is likely to take much longer.
- The process of writing an article for a newspaper is a structured, rule-bound, routine activity whereby a problem is constructed and articulated according to a frame or template (Ward 2005). Common frames are disaster stories, especially with a human victim. The newsworthy aspect of this report is that high-value horticultural crops in the South Australian Riverland were accustomed to 100 % allocations of their water entitlement. To be faced with low current allocations (15 % in 2008) has required a major adjustment. To readers in South Australia, this crisis is seen as partly due to water use in upstream states and a view that, while it is acceptable to use water for high-value perennial crops like wine grapes and citrus, it is inappropriate to use water for high-water-requiring annual crops like rice and cotton which have been traditionally grown in upstream states. There is limited discussion in the popular media in South Australia on the relative merit of annual versus perennial crops with a variable water supply and the fact that little rice or cotton was grown during the recent drought.
- There is a complex relationship between irrigators and the urban society. It should be noted that this article appeared just after Southern Australia had experienced a heat wave in November. This was the first-ever November heat wave for Adelaide. The heat wave had an impact on both the Riverland irrigators and home gardeners. However, despite Adelaide water storages being

full, home gardens were only able to water their gardens two days a week for three hours (the restrictions were changed after this period). There is general support among the urban community for irrigators and recognition that they are victims of a wider system failure. Nevertheless, this support will have limits, which include discussion of whether irrigation is viable in the long term, and contesting water use with the amenity value of home gardens and parks, and the substantial nursery and garden care industry.

The crisis in the Riverland can be repeated in many irrigation communities across the Murray Darling Basin. In his discussion of the history and current crisis in the Murray-Darling Basin, Connell (2005) noted the interaction of three powerful forces: landscape, climate, and society. As a framework to understand this interaction, especially the interaction between irrigation and climate, we have adapted Bawden's (1990) model of four overlapping phases of Australian agriculture:

- *Pioneering phase*. When government built irrigation schemes so that farmers could battle the arid climate with irrigation and *just produce*.
- *Production phase*. When farmers were asked to use the climate and irrigation as resources to *produce more*.
- *Productivity phase*. When the emphasis was on managing irrigation and the variable climate to *produce more efficiently*.
- *Persistence or sustainability phase*. When farmers were asked not only to produce more, produce it more efficiently, but also asked to manage the irrigation for a variable and changing climate to *produce more carefully*.

An essential part of Bawden's argument is that these phases are overlapping. Farmers often still represented as pioneers are asked to produce more, to do so with increased efficiency, and with increased care. The idea that significant amounts of water should be purchased from irrigators for the environment brings competing values of irrigator rights, economic development, environmental concern, indigenous rights, and alternative land use, such as tourism and the future of rural communities (Barr 2009, Chap. 6). This layered complexity is behind the frustration and despair that some irrigators are expressing, and a partial cause of the mixed response the urban community has to the dilemma of how to support irrigation communities and maintain a healthy river.

5.3 The Pioneering Phase: Irrigation as a Solution to Aridity

A principle of drought policy is not to confuse aridity with drought (Lindesey 2005). Aridity is a condition of low rainfall and high evaporation—either on an annual basis as in a desert or on a seasonal basis as in summer in a Mediterranean climate. A farmer complaining of the dry hot summer in a Mediterranean environment is more likely to be told to move than receive drought support. Most definitions of drought involve some notion of a relative rather than absolute shortage of rainfall. After reviewing a series of definitions of drought, the National Drought Review Taskforce (1990) concluded that drought was relative, reflecting a situation whereby there was a mismatch between the agriculturists' expectations of a normal climate and the measured climate at that time.

Europeans arrived in Australia with attitudes and expectations formed by the wet climate of their homeland. As in the United States of America, agriculture in Australia moved from the reasonably humid coastal region to inland regions, and farmers were faced with aridity beyond their imagination or experience. In his book titled, *The Water Dreamers*, historian Cathcart (2009) reviewed the history of trying to solve the problem of aridity, of the explorers hoping to find an inland sea, and being disappointed by the dead heat. Much to the Europeans' disappointment, inland Australia was not a humid environment that suffered the occasional drought; it was an arid environment that had the occasional good season. Cathcart's argument is that Australia has grappled with water and aridity for all of its history, including the current water crisis.

Nicholls (2005) has traced drought as a recurring theme throughout Australian history. He points out that the late 1800s, in both America and Australia, was a time of rural optimism, based partly on the belief that rain followed the plough. In 1881, the official yearbook attributed the run of good seasons to the settlement of the interior, stating with confidence that "droughts are no longer the terror they used to be." This optimism was ill-founded. In 1888, as the centennial celebrations commenced, the worst drought yet seen in the Colonies began. A few years later, a drought commenced that didn't reach the intensity of the 1888 drought—but it lasted a decade. This was the Federation Drought, during which the River Murray stopped flowing. Other major droughts in Australian history are 1937–1945, 1965–1968, 1982–1983, 1991–1995, and 2002–2003.

One approach to aridity was to modify techniques associated with dry farming and dust mulching (Smika 1990; Connell 2005). These techniques of pulverizing the soil to minimize the capillary movement of water were imported to Australia from America around the turn of the century (Fischer 1987; Davidson and Davidson 1993). Techniques such as dust mulching played a major role in the dust bowl and dirty 1930s in the United States and contributed to major soil degradation in Australia (Pratley and Rowell 1987). Another idea imported in part from America was district-wide irrigation schemes.

In the mid 1880s, Victorian Minister Alfred Deakin, who was responsible for water resources, held that if the state of Victoria was "to progress…and use her abundant natural advantages and secure to the agricultural population of her arid districts a permanent prosperity, it would be through irrigation." In 1886, he traveled to the United States and met two Canadians: George and William Chaffey, who had developed a fruit farming community in the California desert. He persuaded them to come to Australia where they started to set up an irrigation scheme in Mildura and also in Renmark in South Australia. The Chaffeys prepared land for irrigation, sold it in blocks on time payments, and used the revenue for further development (Evans 1973; Connell 2005). However, the bank crash of 1893 and the droughts of 1902 and 1914 almost ruined the scheme (Evans 1973), but these schemes are what formed and sustained the towns. Along with the paddle steamers and river transport, the pioneers and subsequent soldier settlement schemes are an important part of history that explains current agricultural and social structure of Riverland towns and communities. Irrigation and river transport had a synergistic effect. The river locks were built to enable all-year navigation, but resulted in permanent water supply which suited irrigation development.

5.4 The Production Phase: Mastering the Climate as a Resource for Irrigation in Arid Environments

Watson (2008) argued that irrigation development has been driven largely by an enthusiasm for irrigation as an ideal in itself. This ideal of irrigation was strongly held by many in Australian government, science, and industry. Arguments cautioning people on irrigation schemes by economists such as Davidson (1969) were seldom heeded. Cathcart (2009) details the treatment of Griffith Taylor, who in the 1920s drew attention to the limits of development of inland Australia and was given the clear message that an optimist was a patriot, a pessimist a traitor. The writer and poet Henry Lawson (1867–1922) wrote of the 1888 drought. “Beaten back in sad dejection/After years of weary toil/On the burning hot selection/where the drought has gorged his spoil.” He then wrote in *The Watch* newspaper, “These Bush people must be helped wholesale—by the Government, by the public, by the people. Every spare penny should be spent on water conservation and irrigation, in sinking tanks and putting down bores, in locking our thousands and thousands of miles of rivers—almost at sea level—where oceans of water waste away after each flood. To attend to these things is a national work for the benefit of the whole nation; to neglect them is a national crime—it is suicidal.” This later piece is quoted by the “Water4Food”[1]campaign for assistance to irrigators, led by a number of local governments that reinforce the point that the pioneering and production phases are ongoing.

In one sense, irrigation can be seen as a means of transforming the arid interior into the more humid climate of the coastal regions. However, there are many production advantages to adding water to an arid environment. Loomis and Conner (1996) noted that most large irrigation schemes are in arid regions of mid-latitudes, where the high level of incoming radiation can be harvested. Compared to more humid environments, sunlight is not limiting and importantly the irrigator controls the supply of water, hence, avoiding the spoiling impact of rain at the wrong time. In addition to abundant radiation and temperature that was rarely limiting to growth, the “light-textured soils of the Riverland are well drained, which

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[1] http://www.water4food.com.au/news/No.water,.no.food.htm

minimizes periodic oxygen deficiency arising from water-logging of the rootzone," Maschmedt (2005; p 56). The low rainfall, high evaporation and quick-draining soils lead to minimal delays for activities, such as spraying, pruning, and mechanical harvesting.

A major attraction of irrigation to government was the opportunity for closer settlement (Randall 1981; Watson 2008). Irrigation has always had a close relationship with the immediate rural community and has allowed the development of services and communities in regions that would otherwise be sparsely populated.

5.5 Productivity Phase: Managing Irrigation and the Variable Climate to *Produce More Efficiently*

Randall (1981) distinguished between phases of water economics; an expansionary phase (similar to the pioneering and production phase) and a mature phase (similar to productivity and persistence phase). Under the expansionary phase, water is cheap and plentiful, the infrastructure costs are largely covered by government schemes and costly maintenance of infrastructure along with environmental impacts, such as water tables and salinity are not yet apparent. The mature phase is characterized by rising costs of water, more direct and intense competition between users (including new users such as the environment) and a heightened awareness of externalities.

The term "water use efficiency" has become common with a range of definitions. Walker et al. (2005) notes that the term has become a generic label for performance indicators for improvements that maintain or increase production for less water. An emphasis on efficiency and water trading also suggests that water should be used for the highest value. Meyer WS (2005) calculated that using water to irrigate pasture for beef and sheep production generated less than $100 per ML. Rice, dairy, and irrigated wheat generated up to $200/ML; cotton generated more than $500/ML; fruit, nuts and grapes generated $1,700/ML; and vegetables generated $3,000/ML. These numbers will change, depending on commodity prices and costs, but they lead to a conclusion that there will always be a set of enterprises that will be able to compete strongly for water against enterprises that find their comparative advantage in selling water as soon as the price is high. Between 2000 and 2001, and 2004 and 2005 when water was scarce and the price high, water used on rice was reduced from 2,200 to 600 GL, and water on cotton reduced from 3,000 to 1,800 GL. At the same time, water used on grapes increased from 600 to 700 GL (Jones 2010). The summer of 2007–2008 saw the lowest rice harvest ever and the fourth highest grape harvest.

In response to the continuing drought, irrigators in Southern Australia adopted a number of strategies, mainly related to first improving their on-farm water use efficiency and then buying water (Mallawaarachchi and Foster 2009). As a resource such as water becomes scarce, there is a greater interest in understanding and minimizing the losses. In the journey from dam to crop, transpiration water can be lost through evaporation during conveyance, seepage and leakage, evaporation during application, evaporation from the soil, transpiration from weeds and cover crops, run-off, and deep drainage below the root zone. Meyer WS (2005) estimated that 10–30 % of water diverted from rivers is lost before it reaches the farm gate. A further 20 % of what is delivered to the farm edge is lost in distribution channels on the farm. A further 10–15 % is lost through over-watering (60 % of irrigation used on farms is applied through flood irrigation and aerial sprays). Table 5.1 provides a summary of the different components of water use efficiency and opportunities for improvement.

Stirzaker (2008) described the complex relationship between the technology developed by scientists for irrigation scheduling and the tacit experiential knowledge of an irrigation farmer. Wine grape production is one of the industries that has the highest adoption rate of irrigation scheduling. A survey of wine grape growers in the Riverland found that more than 70 % were using regulated deficit irrigation, which involves withholding water from the vine to control vegetative and reproductive growth in response to quality specifications from wineries. The increase in efficiency in deficit irrigation is similar to the more complicated partial root zone drying (Sadras 2009). More than half of Riverland vineyards reported irrigating at night to avoid evaporation and varying the irrigation method to weather conditions. Irrigation scheduling seems to be widely used, as 70 % of respondents used capacitance probes and 45 % used tensiometers (Spencer and Ashton 2003). These figures are much higher than the adoption of soil water monitoring tools in Australia, which increased from 13 % to around 25 % between 1996 and 2003 (Chapman et al. 2007). Figure 5.2 shows the changes in irrigation system on a 270 ha commercial vineyard in the Riverland. Over a period of about two decades, the vineyard has switched from predominantly spray irrigation to completely drip. Using an estimate of $5,000/ha, this is an investment of $1.35 million. Figure 5.3 shows that across the vineyard as a whole, production has been maintained or improved, whereas, the amount of water has been reduced from 10 to 11 ML/ha in the early 1990s to less than 6 ML/ha. This resulted in an increase of irrigation water use efficiency across the vineyard of about 1.6 t/ML in the early 1990s to 3.6 t/ML in 2009–2010. This improved efficiency is accompanied by increased quality, due to better control of water through key phenological stages of the wine and easier access for timely spraying operations.

Efficiency gains both on-farm and off-farm are politically appealing, and considerable private and public funds have been invested to improve efficiency. However, the effectiveness of public funds for irrigators to adopt more efficient measures was questioned by the Productivity Commission (2009). As outlined in Table 5.1, across the basin, the water gained through these efficiency measures is often expensive, relative to the cost of water on the market. In most cases, the water gained through increased efficiencies has been used by the farm enterprise to expand their plantings. Only in rare cases has it been used for environmental flows.

Table 5.1 Components of water use efficiency and improved opportunities from Meyer WS (2005), Khan et al. (2004) and Walker et al. (2005)

Off- farm conveyance efficiency The ratio of water leaving the storage source to water delivered to the farm edge	In the current drought considerable political attention has been paid to losses in delivery due to losses from open channels in gravity fed systems. Losses are due to evaporation, seepage from walls and floors of the channel and leakage from physical breaks in the channel. Some of this attention is due to the very high conveyance efficiencies in South Australia where water is moved in pipes (due in part to high conveyance losses in lighter soils). This loss is apparent to the general public driving through irrigation districts. Estimates of capital costs of reducing these losses are high and vary from $500 to $4,000/ML (Meyer WS 2005). If the seepage and leakage is into good-quality aquifers, the loss is more apparent than real as this water will recharge the aquifer. From modeling on the Murrumbidgee Irrigation Area, the greatest gains (100–200 GL) are likely to come from better monitoring and delivery of water within the existing channel system so water is delivered to farms when needed rather than longer durations in channels. Sealing of leaking channels was estimated to save 10–50 GL, and piping channels 15–70 GL
On- farm conveyance and storage efficiency The ratio of water arriving at farm edge to water delivered to the irrigation field	There is a stark contrast visiting a farm where water is moved in pipes for a pressurized irrigation system to one where water is gravity fed by channels and stored on farm dams. The losses from these channels and storage systems can be considerable. Because they are used intermittently, the loss at a point in time can be high, but the total loss is less. As with off-farm conveyance, some of the water that is lost is picked up in the groundwater system and returns to rivers and streams or is pumped directly from groundwater. Meyer WS (2005) calculated that the cost of covering on-farm storage as greater than $295/ML
Field irrigation application efficiency The ratio of water applied as irrigation to the water delivered to the target rootzone	Soil type, crop type and history have led to different irrigation systems. The pressurized systems are the most water efficient, but lateral move irrigation system costs are $1,500/ha, center pivot costs from $2,000/ha to $2,500/ha and drip irrigation is about $5,000/ha (Meyer WS 2005). The efficiency of flood irrigation has been improved by laser leveling and improved monitoring. For horticulture in the Murrumbidgee region, laser leveling is likely to lead to gains of 0.1 to 0.4 ML/ha, compared to well managed laser leveled flood irrigation, savings from center pivot and lateral move were estimated to be 0.4–0.8 ML/ha, and drip irrigation 2–3 ML/ha (Meyer WS 2005). In a vineyard or orchard there is significant scope to minimize evaporation from the soil surface through the use of mulches, shading by the canopy, targeted surface irrigation and subsurface irrigation (Walker et al. 2005). As discussed in more detail later, there is a requirement for some drainage from the bottom of the rootzone for leaching of salt applied in the irrigation water

(continued)

Table 5.1 (continued)

Transpiration efficiency The ratio of water applied to the rootzone to the water transpired by the plant	The main advantage of pressurized irrigation systems is the ability to match the supply of water to crop demand through irrigation scheduling. Costs vary from \$3/ha per year for tensiometers and gypsum blocks to \$22/ha for neutron probes and capacitance sensors and using local weather information (very low cost if available). Transpiration efficiency is also influenced by variety, rootstock, water deficit and salinity, leaf shading and crop nutrition (Walker et al. 2005)
Harvest index The ratio of harvested yield to total crop biomass (yield and mass of other plant parts)	In contrast to say a wheat plant, determining harvest index in perennial horticulture is challenging. It is difficult to assess the amount of biomass partitioned to the root and trunk on an annual basis. Walker et al. (2005) note that harvest index can only be compared when the pruning system is consistent. Harvest index varies between rootstocks, water use, and management practice. In high-value horticulture, the quality of the yield is of greater importance than the quantity and, hence, biomass and harvest index are manipulated for appropriate levels of stress

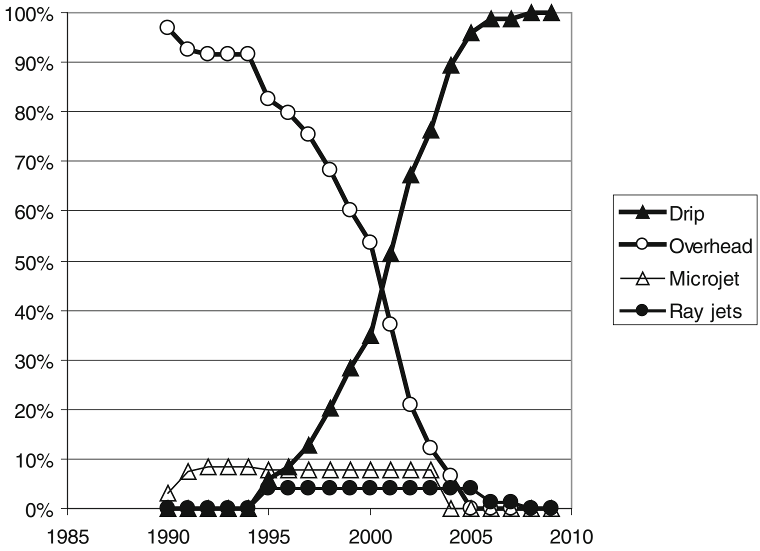

Fig. 5.2 The proportion of a 270 ha commercial vineyard in the Riverland under different forms of irrigation from the 1989–1990 season to the 2009–2010 season. Note the vineyard has changed from no-drip irrigation to completely drip irrigated. Data provided by Yalumba Wine Company

5.6 Persistence Phase

Although all phases are overlapping, Bawden (1990) observed that the pressure on farmers to produce more carefully seldom came with any reduction in pressure over the total level of production or the efficiency of production. Few would argue against productivity growth, as it has been the main way of maintaining and improving international competitiveness. Productivity gains have been a means of offsetting declining real prices received for farm commodities on global markets. Productivity growth in agriculture can also mitigate the adverse effect of other long-term challenges, such as sustainable water use and climate change (Productivity Commission 2009). However, Walker and Salt (2006) use ecological principles to argue that efficiency in a narrow sense with a focus on elimination of redundancies can lead to a rapid reduction in resilience.

Examples of the trade-off between efficiency and resilience relevant to wine grape production in the Riverland are: First, a sense that having made efficiency gains in previous decades and running tight operations both on and on farm, that there is little slack to absorb cuts to water allocations. Second, highly efficient irrigation that eliminates drainage can lead to a build up of salt in the root zone (Stevens 2002). Third, the move to deficit irrigation and minimizing water use through smaller canopies seems to have penalized some growers in recent heat waves (Hayman et al. 2009; Webb et al. 2009) through negative impacts on

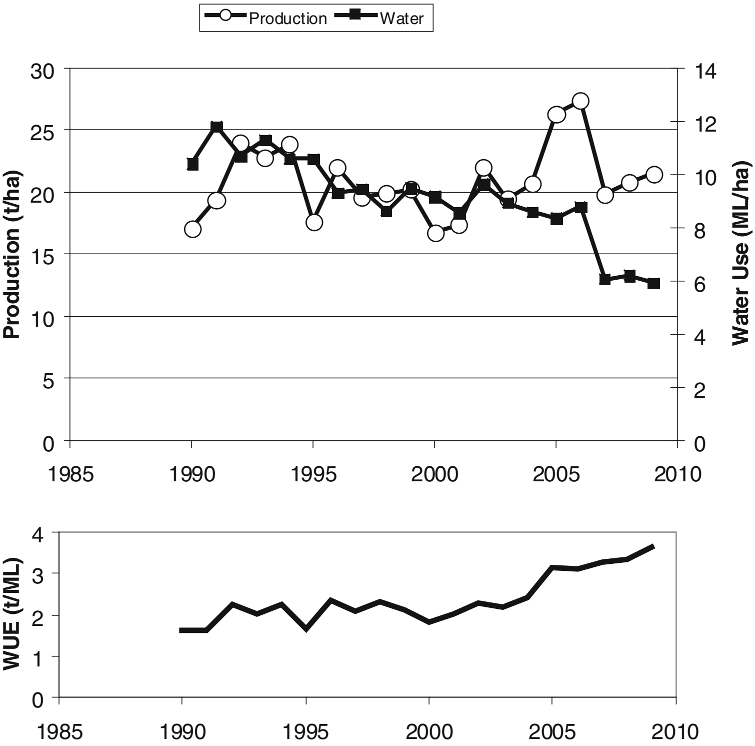

Fig. 5.3 Changes in production (t/ha), water use ML/ha and Water Use Efficiency (*WUE*) (t/ML) for the 1989–1990 season to the 2009–2010 season for the same 270 ha commercial vineyard in SA Riverland as in Fig. 5.2. Data provided by Yalumba Wine Company

wine-grape quality. As discussed in more detail later, deficit irrigation can also accelerate the build-up of salinity in the root zone.

The responses of 20 members of the Riverland Viticultural Technical group to a February 2007 survey regarding their greatest concerns related to climate change are shown in Table 5.2. The quality and quantity of water and extreme heat events were ranked the highest followed by frost and soil salinity, increases of mean temperature was of less concern.

In a discussion on the results of the survey, the viticulturists in the Riverland reinforced the importance of water. Not only did water rank first and second, managing heat waves (ranked third) and frost events (ranked fourth) relied on access to water. Furthermore, soil salinity (ranked fifth) is managed by a leaching irrigation. Historically, the river and wetland environment has tended to receive water when the needs of cities, stock and domestic supplies, and irrigators' needs are met. Increasingly, environmental and recreational water uses are seen as legitimate, in part, for their own sake and, in part, because a healthy river is essential for irrigation. Barr (2009) used this change in hierarchy of water use under scarce conditions to illustrate shifts in underlying values of urban and rural communities.

Table 5.2 Response of 18 members of the Riverland Viticulture Technical group to a series of potential changes in climate. The lower the number, the higher the rank. The rank is out of 15. Survey held in 2007

Potential climate change	Rank
Change in quality and quantity of water	
Increase in soil salinity	5
Decrease in quality of ground water	14
Decrease in volume of ground water	13
Decrease in quality of surface water	2
Decrease in volume of surface water	1
Changes to rainfall	
Increase in the intensity of rainfall	9
Decrease in autumn rainfall by 15 %	10
Decrease in summer rainfall by 15 %	15
Decrease in spring rainfall by 15 %	6
Decrease in winter rainfall by 15 %	6
Decrease in annual rainfall by 15 %	6
Changes to temperature	
Increase in heat waves	3
Increase in extreme min temp events—frosts	4
Decrease in extreme min temp events—frosts	15
Increase in average day temp by 1 or 2 degrees	11
Increase in average night temp by 1 or 2 degrees	11

It is simplistic to overlook the concern many irrigators have for the health of the river environment. This is likely to be a mixture of enlightened self-interest as irrigation requires a healthy river and a valuing of environmental assets for their own sake. Irrigators have long been aware of off-site impacts and have worked with scientists to monitor solutes in the root-zone to assist with identifying leaching requirements if there is a build up of salt. They also monitor cases of over irrigation with nitrate at depth (Stevens 2002; Stirzaker 2008). Dealing with salinity and water for river health presents a significant challenge for irrigators in a variable climate. In the current drought, water quality in the Riverland (but not downstream in the Lower lakes) has been reasonably good (0.2–0.3 dS/m compared to a longer term average of 0.4–0.6 dS/m). This is because the primary source of the water has been the upper reaches of the catchment, and the widespread drought has resulted in relatively little saline drainage from upstream. In the future, interaction between quality and quantity of water is likely to be problematic, especially in low water supply years (Connor et al. 2009). As described by other authors in this volume, the Murray Darling Basin seems to be experiencing a reduction in streamflow, consistent with projections of climate change (Kirby et al. 2013). From a study of the impact of climate change on the Murray Darling Basin, Connor et al. (2009) found a reduction in total area irrigated and decreased investments in efficient irrigation. As noted earlier in this chapter, investments in efficient irrigation are expensive and have in the past been offset by expanding the area irrigated. A contraction of irrigation on individual farms leads to less income to cover fixed costs. Likewise, a contraction in a region leads to fewer enterprises to cover the costs. Connor et al. (2009) also found that increased variability and risk of low-water allocations shifted planting from perennial to annual crops.

5.7 Conclusion: Drought and Aridity—Fast- and Slow-Moving Variables

The distinction between drought and aridity is usually made with the assumption of a stationary climate, whereby, climate is a random walk of variability surrounding a mean. This involves an acceptance that climate fluctuates, but also an understanding (not always explicit) that these fluctuations are within an envelope of variability (Jones 2010). Drought is a shock that is at the extreme end of the variation and punctuates what is considered normal (Blench and Marriage 1999). Milly et al. (2008) observed that accepting non-stationarity of climate challenged the basis of planning and risk assessment that permeated training and practice for water engineers. The agricultural risk assessment that most irrigators and advisers have been exposed to recognizes that climate is variable, even cyclical, but over a long enough period assumed to be stationary. In many cases, this may be a reasonable assumption, but climate change will challenge this in the future, and observed decadal variability means that it was always problematic. Indeed, quite apart from climate change, a feature of the Murray Darling Basin is the high degree of development in the latter half of the twentieth century, which was much wetter than the first half (Jones 2010). Some of this also can be explained by ocean–atmosphere phenomena, such as the Interdecadal Pacific Oscillation (Power et al. 1999).

In the context of drought and farming, Stafford-Smith et al. (2007) drew attention to a core concept of resilience theory of distinguishing and treating underlying slow variables rather than the more obvious fast variables. The example he used was a drought bankrupting farm families living on an eroded landscape with no stored capital. The drought is the fast variable, the long-term degradation and non-viable farming is the slow variable. Treating drought will not solve the problem of viability. For wine-grape growers in the Riverland, the drought has coincided with a readjustment in the world wine supply and demand. For all irrigators, the drought has highlighted the problems of an over-allocated system. A feature of droughts as a fast-moving variable is that they have an end, and this is why many irrigators hope that this is just a drought. The worry is that the slow-moving variable may be increasing aridity associated with climate change—a case of drying rather than drought. This chapter started with the description of the crisis and exodus, but while the focus of policy is on the irrigators who are leaving, more are wanting to stay and adapt to both the fast-moving variable of critical droughts (which are likely to become more common) and the slow-moving variable of increased aridity.

Dealing with an uncertain future requires adaptive management, which entails a shift from “knowing” to “learning.” Irrigation communities and those working with them need to be adaptive and learn as we move into a new future. One of the challenges is to work out what parts of the history to carry forward and what parts to abandon.

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Chapter 6
Irrigation Associations Coping with Drought: The Case of Four Irrigation Districts in Eastern Spain

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Abstract The aim of this article is to analyze the strategies developed by water users' associations in Spain to overcome drought in a context of structural scarcity due to geographical conditions and from the development of expansionary irrigation policies. This analysis is based on interviews with farmers and representatives of water user's associations in four selected irrigation districts placed in the Valencia Region. The work demonstrates that in a relatively small area of the Mediterranean there are very different levels of vulnerability, generally related to the origin and diversity of water resources. Diversification of resources and hydraulic interconnection of districts, which allows for water management flexibility, appear to be the best way to improve drought resilience in the area. However, some institutional and environmental risks of these strategies are also outlined.

6.1 Introduction

The broad diversity of climate and agriculture on the Iberian Peninsula entails different meteorological, hydrological, agrarian, social, and economic droughts (Wilhite and Glantz 1985). Beyond the classical divide between wet Spain and dry

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Spain, present in both the National Water Plans and also in school text books, some authors have managed to establish a "diagonal drought line" (Pérez Cueva 1983) that divides the country, depending on the different intensity and recurrence this phenomenon takes.[1] The regions with the lowest rainfall lie to the southeast. These regions also record temperatures and hours of sunshine that are more suited to early planting (fresh fruit and vegetables) and, generally speaking, to production frameworks that yield more economies of scale. The persistent application of a management model based on the mobilization and supply of water has fuelled significant growth in the surface area of irrigated land, which has played a key role in the economic development southeast of the peninsula. The growth in demand triggered by the expansion of irrigation has on many occasions surpassed the threshold of sustainability of local and regional water resources, causing serious damage to water bodies and their associated ecosystems.

In this scenario of enormous pressure on the resource, the shortage of water has brought about a structural phenomenon. Water has become the focal point of a bitter political debate, and both the government and users are in the midst of searching for a more efficient way of managing the resource at all levels. Consequently, while droughts are usually perceived clearly in meteorological or hydrological terms, distinguishing between scarcity and drought is more difficult when we consider the analysis of the responses provided by irrigation associations when faced with such periods. Most of the irrigation organizations take various steps on a regular basis to become more efficient and increase their guarantee of supply—measures that on many occasions are inseparable or identical to those aimed at preventing or combating droughts. Droughts, due to the shortage of water in the region, are seen as a recurring but short phenomena and have, in fact, been incorporated into theses users' practices.

In order to describe these periods in more detail, this research examines the responses given by several water users' associations in four irrigation districts in the Valencia region of eastern Spain (Fig. 6.1). Two of them are mainly provided with water from rivers—Lower Jucar and Lower Segura districts. However, the other two—Vinalopó and Vall d'Uixó valleys—use groundwater. Using the information obtained from several interviews with farmers and representatives of irrigation associations and data from regional agricultural statistics, this chapter compares how these communities cope with droughts in very close but contrasting geographical scenarios.

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[1] Several authors have underlined the complexity of this phenomenon and the variety of conditions, influential factors, perceptions and effects. See Pita (1988) and Olcina Cantos (2001).

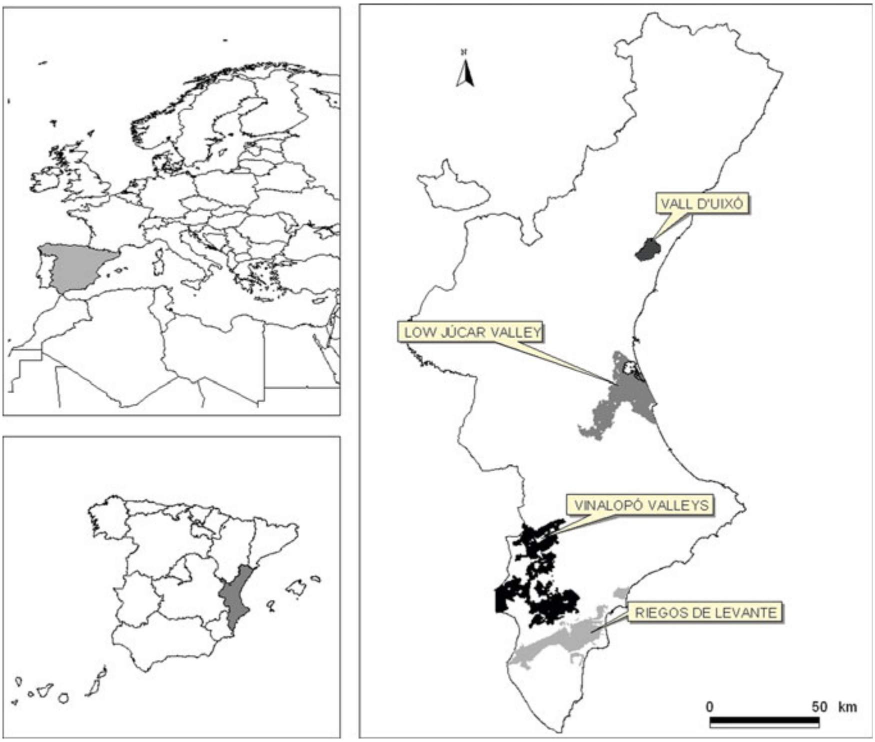

Fig. 6.1 Location of the four study areas

6.2 National Institutional Framework

Drought management in Spain has evolved from a merely momentary intervention on behalf of the concessionary system towards integral, planned, and participative management of the resource.

The Spanish Water Act of 1879 was in force throughout the best part of the twentieth century. This law declared surface water public property along with its use through concessions.[2] It also contemplated the possibility of either authorities temporarily expropriating water concessions to be used in supplies (by compulsory purchase) or reducing concessions during droughts (without compensation).

The Water Act of 1985 later declared all water public property, including underground water, and authorized the government to take exceptional administrative action during droughts to manage water resources. Such measures included

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[2] The Spanish Water Law (article 57) establishes that all the exclusive uses of water require an administrative allocation, granted by the Basin Authority (*Confederación Hidrográfica*), according to the Basin Management Plans (*Planes de Cuenca*), which will be temporary and no longer than 75 years.

reducing the amount of water supplied under concession and concessionary rights for all water uses without compensation, as well as to temporarily use and acquire concessions by compulsory purchase to carry out work, surveys, and studies. A short time afterwards, the government passed Law 9/1996 for extraordinary, exceptional, and urgent measures to solve water supply problems, such as a persistent drought. This law allows the government to review concessions without compensation when the objective of the concession can be accomplished using less water or by way of a technical improvement in the use of the resource that saves water. Likewise, the disciplinary system and sanctions for not using concessions properly were made tougher. The amended text of the Water Act (TRLA) of 2001 (Royal Legislative Decree 1/2001, of 20th July) includes similar content in article 65 to that contained in Law 9/1996. This legislation boosted the implementation of measures to mitigate the effect of droughts, protecting urban uses of water, reducing those volumes allocated for irrigation, and permitting the temporal overexploitation of groundwater.

Directive 2000/60/EC (DOCE L 327 of 22.12.2000), which establishes a framework for community action in the field of water policy (hereafter referred to as WFD), contemplates water management to prevent or reduce the impact of floods and droughts. There may be grounds for exemption (Art. 6) from the requirements to prevent further deterioration of water status or to achieve good status (main objective of the WFD) providing all practicable steps are taken to mitigate the adverse impact on the status of the body of water and that:

- "the conditions under which circumstances that are exceptional or that could not reasonably have been foreseen may be declared, including the adoption of the appropriate indicators, are stated in the river basin management plan;
- the measures to be taken under such exceptional circumstances are included in the program of measures and will not compromise the recovery of the quality of the body of water once the circumstances are over;
- the effects of the circumstances that are exceptional or that could not reasonably have been foreseen are reviewed annually and, all practicable measures are taken with the aim of restoring the body of water to its status prior to the effects of those circumstances as soon as reasonably practicable and a summary of the effects of the circumstances and of such measures taken are included in the next update of the river basin management plan."

Article 27 of the adaptation of the WFD to Spain, the National Water Plan (Law 10/2001, of 5.7.2001) addresses drought management and contemplates a system of global water indicators to forecast droughts[3] and incorporates special action

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[3] The Spanish regulations entail the elaboration of special drought plans in each hydrological demarcation (Confederaciones Hidrográficas and regional water agencies) establishing four levels of normality, pre-alert, alert and emergency. These levels are determined by the Index of state (Ie), which relates the available resources with the historical maximum (1) and minimal (0) levels, attending groundwater levels, reservoirs storage, rainfall and natural river flows (Normality, Ie > 0.5; Pre-alert, Ie 0.49-0.3; Alert, Ie 0.29-0.15; Emergency, Ie < 0.14).

plans into river basin water plans for situations of alert and eventual drought that include system use regulations and measures to be applied in relation to the use of public water property.

The special drought plans for intercommunity river basins, under the jurisdiction of the Spanish state, were passed in March 2007 (Ministry of the Environment Order 1698/2007, of 21st March).[4] This began a comprehensive strategy of action aimed at minimizing the environmental, economic, and social impact of possible droughts. These plans and the rest of the measures included in the legislation involve the Ministry of the Environment, through the confederaciones hidrográficas, but the users' associations—the irrigation communities—are vital stakeholders with respect to irrigation.[5]

The communities of irrigators and other water users' associations are, as acknowledged in the Water Acts of 1879 and 1985, the organizations responsible for managing irrigation on a local scale. They are publicly held companies, attached to the basin authorities—confederaciones hidrográficas—and internally independent with respect to management. They are non-profit organizations devoted to distributing, managing, and controlling the water transferred under concession by the state. These organizations maintain and improve irrigation infrastructures, establish mechanisms to handle the resource and distribute it. They then charge all their members the costs of these services and those related to obtaining the water using various different rate systems. They are also legally empowered to resolve internal disputes among users.

The organizations have representatives in government, administration, and planning of the confederaciones hidrográficas, which include government council, users' assembly, and basin water council, as well as on the key management bodies, such as the operations councils, reservoir committee, and works council. As a result, a permanent coordination exists between the government in charge of providing the resources and water users' associations, thus allowing work and management tasks to be planned. During droughts, a special entity devoted to coordinating management is brought into action, namely the drought committees, in which the administration, ecologist organizations, and the agrarian and urban users are represented.

Our analysis explores how irrigation reacts and adapts to droughts. Therefore, we will initially focus on the steps taken by the public sector, in coordination with irrigation entities. During droughts, irrigation systems are the first to suffer water restrictions. This is because the legislation states that urban and environmental supply and river flows are higher priority than irrigation, and because irrigation accounts for between 75 and 80 % of the demand for water in the river basins with the greatest shortage of water.

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[4] They can be consulted at http://www.mma.es/portal/secciones/acm/aguas_continent_zonas_asoc/ons/planes_sequia_isas/index.html.

[5] For the Spanish water users' associations see: Del Campo (2002), Merino (2006), Sanchis et al. (2009).

The shortage of water is the main problem in south-eastern Spain, and that frequently explains the problems with the quality of water bodies. For this reason, the measures to mitigate the impact of droughts should be addressed in both normal years, by taking part in water planning for the medium and long term, and drought years, which determine the effectiveness of the response in the short term.

In the short term, the most immediate measure is to review concessions. This may be done in proportion to the irrigated land, according to the rights of concession (historical irrigation, new irrigation, irrigation surpluses). The source of water (underground or surface water) and crops (for example, prohibiting irrigation of pasture and grains) also must be reviewed. The percentage the concession is reduced may vary a great deal depending on the severity of the drought, production areas, and crops (for example, concessions for arable crops are reduced more than for woody crops in order to guarantee the survival of trees). One variant of the above is a reduction in the number of gravity irrigation applications.

Concessions to the Jucar River basin were reduced by as much as 60 % during the drought in 2005–2006, and 80 % in the Ebro River basin in the drought of 1983–1985. Another complementary measure adopted frequently during droughts is to increase the control and sanctions of either excessive or unauthorized extractions of water.

The main long-term measures that have been adopted as part of the water plan and affect irrigation are as follows:

Enlargement and improvement of infrastructures. Referring to both storage and regulation infrastructure and aimed at enhancing irrigation efficiency. Although there is a high level of regulation in Spain, the water plans contemplate the possibility of further regulations of limited power in certain regions (particularly in small rivers and streams in the Mediterranean) and some interbasin transfers authorized and managed by the central government. Moreover, financial measures have been set in motion so users can renew their irrigation systems and reduce water losses by concreting channels, installing drip irrigation, plot levelling, improving drainage, etc. These measures are part of huge "modernization" schemes that both the central government, through the state-owned company SEIASA, and also regional governments have embarked upon. Since the 1980s these measures have made an enormous contribution to the transformation of flood irrigation systems to pressurized systems, mainly drip irrigation.

Use of new aquifers and combining or alternating their use with surface water. Underground water, despite the wealth of knowledge gained in recent years, requires more research because of its low relative cost and how quickly it can be used during droughts. The two most widespread measures for years now are "drought wells" (new or existing) and the temporary reduction of concessions. In some regions, opening drought wells restricts their activity during summer, while in others, due to a shortage of surface water the rest of the year, the wells are used year-round. For example, 314 hm^3 of water per year was extracted from the drought wells in the Segura River basin during the drought between 1990 and 1995. However, extractions from underground aquifers during normal periods do not exceed 150 hm^3 per year. This results in a decrease in the piezometric level with a subsequent increase in extraction costs and the salt level of the water extracted.

Increase in the use of non-conventional resources. Over the last few years, irrigation communities, with the financial aid of the government, have incorporated treated wastewater into their annual volume of water. Using water from desalination plants is limited at present to urban supplies and severe droughts, as it is too expensive to use on most crops.

Improvements in the control of water uses. The use of meters has spread among farm users. While all collective or individual users must employ volume meters, they have often not been installed, particularly for underground water. Metering water usage is often ignored with unspoken approval of organizations (for example, the users of the aquifer in the eastern part of La Mancha region) and sometimes due to opposition by the users (for example, the users of the aquifer in the western part of La Mancha region). If we cannot ascertain the amount of water actually used, it is difficult to check whether users are complying with the concession or a possible reduction in the concession during drought.

Development of the operations framework of the Centres for the Exchange of Concessionary Rights, pursuant to art. 7 of the amended text of the Water Act, to be enforced in any drought situation (on standby, on yellow alert and emergency). Some exchanges have occurred between users over the last few years. Voluntary agreements are undoubtedly the least conflictive (they can only damage the minority interests of those who are opposed to the agreements of the irrigation association). Since the 1980s, private agreements have been reached with a similar goal to that of the amended text of the Water Act of 2001. As a result, during the drought from 1983 to 1985 the Andorra Power Station (Teruel) purchased the right to use water from the Guadalope Central Irrigation Syndicate, which abandoned irrigation temporarily. This operation was repeated during the drought from 1998 to 2000.

Similarly, there have been numerous exchanges of water rights between irrigation and urban users, although irrigators on this occasion had little chance of rejecting them due to the fact that, according to the Water Law, the urban water supply has priority over irrigation as a water use. During the last drought in 2008, the Taibilla Association of Channels and River Segura Irrigators on the one hand, and Tajo River Communities of Irrigators (Estremera) on the other, agreed, under the umbrella of the provisions affecting the Centres for the Exchange of Concessionary Rights (CECR) to purchase 30 hm^3 of water from the Guadalquivir River basin and 12 hm^3 from the Mediterranean basin in Andalusia. One of the measures that could and should be applied during times of drought is to activate the CECR. During the recent drought in the Jucar River basin, apart from a reduction in the concession, an agreement on “economic compensation for the total restriction of water use” was reached and was relatively successful in the aquifer in the eastern part of La Mancha.

Application of tax benefits. Tax benefits are normally used to mitigate the impact of a decrease in farm income as a result of a drought. Some are general in nature, such as postponing tax or loan payments or exemptions from certain charges. The latest tax benefits applied, directly related to the use of extraordinary resources, were to exempt from paying a transfer tax (or reimburse them the tax charged) users who acquire temporary water rights from other river basins, wells, or desalination plants. The benefits also result in a reduction in rates for using public infrastructure to transport water from other basins (for example, the Tajo River-Segura River Aqueduct).

All of the foregoing measures, except for use of volume meters and transfers, are accepted without complaints by users, guaranteeing them, as the current legislation does, that they will participate in planning through the participation and consultancy bodies (which belong to both the ministry and the river basin water confederations).

The steps taken during times of drought are obviously more difficult for users to accept, even though their representatives are part of the participation and consultancy bodies (drought committees). This is because the phenomenon will invariably entail losses and that irrigation is behind the water supply and the environment in order of priority.

6.3 Irrigation in the Valleys of the Vinalopó River

The Vinalopó River drains a 1,705 km^2 basin in the province of Alicante, which has traditionally been divided into three sections, known as the upper, middle and lower Vinalopó. Our analysis is confined to the first two valleys, where irrigation is almost exclusively covered by underground water. River resources are scarce and historically could only supply small vegetable gardens in the vicinity of the main towns. At the beginning of the twentieth century, the private sector fuelled a significant increase in irrigated land after pumping technology became widespread. This expansion escalated in the 1950s and 1960 s due to the involvement of the state, which opened numerous wells in order to create new irrigation systems. Nowadays, 19,022 ha of land is being irrigated, which includes primarily grapevines and olive groves, managed by 26 water users' associations and various private users.

The increase in irrigated land, growth in urban demand, and the transfer of resources to the coast of Alicante increased extractions remarkably, easily exceeding aquifer recharge rates (Rico Amorós 1994; Bru 1993). The fall in water table levels and the saltwater intrusion of wells has resulted in irrigation reaching a critical situation in these districts, particularly in some areas of the middle Vinalopó, where underground resources are scarcer. The case of the municipality of Aspe, where irrigated land has decreased from 2,800 to 750 ha in 20 years, due to the abandonment of the agrarian activity, is an excellent example of the crisis suffered by this operating system.

In both districts, meteorological and agrarian droughts—using Wilhite and Glantz (1985) concepts—coincide almost exactly, due to crops depending practically exclusively on local underground resources. Irrigators normally respond immediately when faced with a decrease in rainfall by increasing the number of extractions and the amount applied to each field.

Consumption on behalf of irrigation organizations in dry years increases by around 25 % with respect to normal years, according to data obtained from the various sectors in the basin. This scenario, in which aquifers are being overused, accelerates the decline of water tables and shortens the useful life of wells. During the 1994–1995 drought, the piezometric levels of the Yecla-Jumilla-Beneixama aquifer recorded decreases of more than 14 m. Over the last 30 years, the piezometric level of the aquifer has fallen by 3.2 m a year on average (Martínez Espinosa 2004).

The increase in energy consumption logically raises production costs. Extraction costs are passed on to irrigators by way of a rate per-unit of volume consumed that is set at the beginning of the season. Therefore, a drought increases the final cost of irrigation per-unit of land in most water users' associations by between 20 and 25 % with respect to years considered normal. However, this does not trigger an increase in the price of water until the following year's exercise. Only three associations in the upper Vinalopó have implemented progressive rate-setting systems that penalize high consumption. Notwithstanding, these measures are not aimed at reducing an association's overall consumption, but rather at preventing a concentration of water demand at certain times of the year. The measures are designed to avoid pumping at times of the day when electricity costs are highest. Such peaks in demand, moreover, are not normally caused by farmers who own irrigation ponds and plan their season appropriately, but by the multitude of users who have gardens and swimming pools and record high levels of consumption at the beginning of summer.

In these areas supplied by overused resources, a large proportion of the economic effects of droughts do not only appear during the drought, but are also felt in later years, in which the decrease in water tables increase extraction costs and push up the price of water established by irrigation organizations. In the middle Vinalopó, water prices in some organizations have surpassed 0.40 €/m^3, which makes it extremely difficult for farms to be commercially viable. Such organizations sometimes use wells located at a depth of more than 500 m.

In order to cope with the lack of rainfall and the structural shortage of water resources, irrigators have used various strategies in the last few years in their search for new resources and improvements in technology, management, and crops. The search for new resources, after some wells dried up, has been constant throughout the recent history of these irrigation organizations, particularly in the middle Vinalopó. In this sense, unconventional resources have been incorporated over the last decade, mainly treated wastewater. No significant treated wastewater was used between both districts during the drought of 1994–1995. However, over the last few years, in order to increase their guarantee of supply, middle and upper Vinalopó irrigators have captured the effluents of several wastewater treatment plants, reutilizing around 7 hm^3 a year.

Despite a considerable number of organizations having concessionary rights to use these resources, they are not all using them, due to effluents not being of sufficient quality. Irrigators offer three reasons these low-quality resources cannot be used. First, wastewaters often block the droppers used in pressurised irrigation;

second, farm managers—mainly of vegetable farms—are limiting the use of wastewater locally, due to the fear of the low-quality water affecting the marketing of their products. Finally, the presence of numerous second homes that are supplied drinking water by irrigation organizations makes it impossible nowadays to make the use of this resource widespread in some communities. Nevertheless, some organizations have begun to build separate networks in order to incorporate these flows into the irrigation system, which suggests they will be used more in the future.

Vinalopó irrigators have their hopes placed on the arrival of flows transferred from the Jucar River, a claim that dates back to the fifteenth century. The transfer has been the object of heated debate between those in favor of the transfer and those against it, in the wake of disputes over the reform of the National Water Plan. The Jucar-Vinalopó transfer was approved in 1997, work began in 2003, but the new government approved a change of intake in 2005, moving it to the river mouth. The change satisfied the demands of the irrigators in the Jucar basin, concerned about the decrease in river flows, but to the detriment of final users, because the quality of the water at the new intake was lower. The project was completed in 2012, and several agreements have been reached between the parties involved to make the transferred water drinkable. The irrigators in Vinalopó hope these contributions will reduce their secular shortage of water and guarantee the recovery of their aquifers.

Furthermore, irrigation bodies in the district have made huge investments over the last few years, with the help of the state, which has markedly enhanced the efficiency of irrigation systems and simplified some operating procedures for handling water. In the first place, the irrigation organizations in Vinalopó have substantially increased their reservoir capacity, which 20 years ago barely accounted for 3 % of average annual consumption of irrigation associations. Nowadays, the figure approaches 20 %, and some communities of irrigators have regulation basins that represent more than a third of annual consumption. In this sense, the commitment of the administration to co-financing these initiatives has been vital. The ring of reservoirs that is part of the post Jucar-Vinalopó transfer work plan has been decisive in the improvement of these organizations' regulation capacity.

However, the most important change addressed in recent years was the widespread implementation of pressurized irrigation systems. The communities of irrigators have executed this project in stages, mainly making use of the regional government's funding plans, and have now transformed nearly 90 % of the irrigated land in the district. This transformation has brought about a substantial change in the way water is handled in the area. The most noteworthy change is the abandonment of water distribution procedures by turns and water auctions, an aspiration that irrigators have had for several decades. Water is now distributed on demand in all the associations in the district, and night-time irrigation by flooding has disappeared. Both the modernization of the irrigation system and greater guarantees of supply have contributed to this result.

Despite the government stating that adopting these irrigation techniques saves water, the main reason that irrigators changed the irrigation system—in this area and in others in the region—was not to reduce consumption, but rather to improve production costs, as a result of the advantages gained through fertigation and the decrease in labor costs. In fact, in the case of Vinalopó, the organizations for which it has been possible to compare annual consumption data prior to the transformation with current data do not register a significant decrease in unit consumption. Other factors, such as the long period of time that water remains in the new reservoirs or the existence of farmer inertia, in which the amount of water applied to the plant is concerned, may explain this situation.

Together with these technical improvements, institutional reforms have also taken place, reducing the cost of managing this resource. The most worthy to note was the transfer of the wells opened by the state which, since the early 1980s, had been run by the regional government. In 1984, this government raised the price of using these facilities by 22 %, which led some associations to begin talks and negotiations in order to create a district-wide association to put pressure on the government over its price-fixing policy. As a result, in 1988 the Asociación Comarcal de Sociedades Agrarias de Transformación y Comunidades de Regantes del Alto Vinalopó was officially created in order to obtain the direct management of the wells and, hence, reduce their costs. This district association, initially made up of 10 irrigation associations and two town councils, was the forerunner of the Comunidad General de Usuarios del Alto Vinalopó (General Community of Users in the Upper Vinalopó in English), which was founded in 1996. In total, this community currently comprises 23 irrigation associations, 21 private users—community properties, public limited companies and limited companies, etc.—and 13 town councils. Finally, in May 1998, the CGUAV was officially transferred the rights to run the 24 wells in the district, arranged in seven groups, thus fulfilling the main objective for which it was created.

Over the last few years, some irrigation associations have also merged in order to rationalize irrigation management and enhance efficiency. In some areas of the basin, several small water users' associations were present. This situation is common in Spanish underground irrigation systems, in which irrigation associations have proliferated as a result of private ownership of underground water persisting for a long time. For example, the Villena Irrigators Community was created recently to this end; eight associations have already become members, and the new community hopes to incorporate another three from the same municipality in the future. One factor that influenced such mergers was the prior execution of projects to connect the infrastructure of the irrigation associations, favored by the undertaking of the post Jucar-Vinalopó transfer work plan. Network pressurization work was also decisive in these unification processes, in order to avoid irrigators belonging to associations that already had drip irrigation having to finance the infrastructure of the areas they were about to join.

6.4 The General Community of Vall d'Uixó

The municipality of Vall d'Uixó is located in the district of La Plana Baixa in the province of Castellon. Farms in the region irrigate their land exclusively with underground water from hydro-geological formations. This water is considered insufficient to meet demand, at least since the 1980s, resulting in extracted water having a high level of salt (Barba-Romero et al. 1998). Total irrigated land supplied by the irrigation associations that make up the General Irrigators Community in Vall d'Uixó amounts to 2,822 ha, theoretically all of the irrigated land in the municipality. The Confederación Hidrográfica del Júcar (CHJ) has stopped any further extractions from being made since the mid-1980s and, as a result, has also prevented irrigation from spreading. Following a decrease in the last few years, irrigated land in the municipality totals around 2,100 ha devoted to growing citrus fruit, primarily mandarins.

All the water used for irrigation in the municipality is managed by collective organizations. These communities existed prior to the current Water Act of 1985 and, for this reason, underground water is managed privately. The general Irrigators Community of Vall d'Uixó was created to regulate the use of underground water in the municipality. All the civil societies and irrigation cooperatives in the municipality are members. The shortage of water and the progressive increase in water salinity as a result of using the aquifer was the reason this community was created, following the suggestion made by the Confederación Hidrográfica del Júcar.

The associations that are members of the General Irrigators Community are in charge of managing most of the water for irrigation purposes in the municipality by using underground resources in the region and other resources, such as winter surpluses from the San José spring and treated waste water (4,600 m^3 a day, equivalent to a maximum of 1.6 hm^3 a year).

The General Irrigators Community currently has 3,996 members who irrigate a total of 5,500 farms. This is a good illustration of the smallholding in the area, as it means that each member has 0.62 ha of land and 0.45 ha per plot. The 12 organizations that currently make up the general community have 56 catchments in the municipality, of which 44 are in use. The total volume of water registered amounts to 19.9 hm^3, while the sum of flows taken by all the organizations amounts to 2,053 l/s. Pump depths range from 37 to 250 m in these catchments.

Until 2001, when the process to modernize irrigation began, all associations organized irrigation in a similar way. Associations or cooperatives used their own channels to distribute water to their members. Irrigation was supplied when requested by farmers, no turns being taken. Whenever any members of the general assembly of the General Irrigators Community proposed to make it obligatory for irrigation communities to force associations to take turns to file their irrigation requests, the move was rejected by the majority. The system used then was irrigation by flooding with dikes. Drip irrigation began to spread following individual projects on large farms and the initiative of some associations. Irrigation associations did not have adequate water measuring systems, meaning there was no objective control of consumption. The irrigator from each association only controlled the number of hours of irrigation of a theoretical amount of water, normally greater than the real figure. This made it possible to approximate the theoretical consumption of irrigation water for each plot.

With regard to the collective associations that used underground water that were created before the Water Act of 1985, irrigation rights were obtained by acquiring shares. In some cases they were linked to the land (cooperatives) and in other cases they were not. Shares give farmers the right to irrigate a given surface area. The amount of land that can be irrigated is determined in each association and based on the effect it has on irrigation efficiency. Farms in the region transformed their land into irrigated paddies and purchased the necessary shares from one association or another, thereby determining the irrigated land under the jurisdiction of each association. Then, infrastructures were built to irrigate the paddies of the farmers who owned the shares. Consequently, the resulting irrigation network saw channels cross over each other and duplicate routes, considerably reducing efficiency and causing more than a few problems for water management. The management model of associations with underground water causes these situations, as it is the association itself that decides independently and individually how much water should be extracted from an aquifer. The association can increase its number of users by merely issuing more irrigation shares.

In 1997, the *Centro Valenciano de Estudios sobre el Riego* (Valencia Center of Irrigation Studies in English) carried out an in-depth study of irrigation in the region. With regard to estimated consumption, the average for the 11 associations studied amounted to 10,957 m^3/ha per year. However, average consumption differed markedly from one association to another, ranging from 5,873 m^3 to slightly more than 11,000 m^3/ha. Additionally, 18 different associations managed irrigation in an area of little more than 2,500 ha—an average of 130 ha per association—gave rise to a complex and inefficient irrigation network.

Statistical information regarding the land occupied by crops at a municipal level reveals that arable crops account for a very small proportion and that during droughts, no significant variations occur in the amount of woodland crops being irrigated. During droughts, farmers maintain their level of irrigation, increasing the pressure on an already overused aquifer. The resulting increase in scarcity also increases water salinity, which, despite not affecting the surface area occupied by crops, had an impact on citrus fruit harvests.

As a result of the high degree of inefficiency in the use of water, which was steadily depleting the aquifer and deteriorating water quality, irrigators decided to modernize the irrigation network by installing drip irrigation. All of the associations in the municipality, except for two small communities, implemented drip irrigation. Drip irrigation now covers more than 93 % of total land that can be irrigated. The process itself has helped to improve some of the problems that made water management in the municipality inefficient. The number of associations that managed irrigation water in the municipality has been reduced from 18 before the modernization took place, to 12 at present. Although this number remains high, water use efficiency has been enhanced by sharing available resources and facilities. The associations that have merged are the ones whose irrigation networks were the most intertwined. This has made it possible to abandon the use of 12 of the wells with the saltiest water. The modernization project was what triggered such mergers.

The General Irrigators Community continues to carry out administrative duties and represents irrigation associations before the government, but does not manage irrigation water. However, it does offer services to its members, including engineering, supplies, etc. According to data from the General Irrigators Community, in 1989 there was a total of 2,932 ha of irrigable land. However, this figure dropped by 16.1 % in 2008 to 2,461 ha of which only 1,974 ha of land is actually irrigated. Over the last few years, a remarkable decrease in the surface area of irrigated land has occurred due to farmland being converted into land for urban development (housing estates, industrial parks, roads and other infrastructures). The price crisis in citrus produce may have played a role in farmland being abandoned.

The regional government financed the installation of drip irrigation with grants amounting to around 40 % of the total investment. The total cost of modernizing the irrigation network was approximately 5,300 €/ha, of which farmers paid 3,180. Following completion of the modernization process, unit consumption decreased remarkably. Consumption fell from an average of more than 10,000 m^3/ha in the 1990s to an average per hectare of 4,000 m^3/year. Only the two small associations that have not modernized their infrastructure record significantly higher figures. The San Pedro Irrigators Community consumes around 8,500 and the Uxó Irrigation Cooperative consumes more than 20,000 m^3/ha The modernization process has resulted in an improvement in the piezometric levels of the aquifers that are used to supply irrigation communities, as verified by Confederación Hidrográfica del Júcar (2009). However, significant decreases in the level of salinity of the water extracted have not yet been observed.

6.5 Traditional Irrigation in the Lower Jucar River

Traditional irrigation in the Jucar River is spread across 40,000 ha of land. Almost half of this area is supplied by the *Acequia Real del Júcar* (Jucar Royal Irrigation Channel in English)—19,000 ha—while the irrigation channels of the water users' associations in Escalona, Carcaixent, Quatre Pobles, Cullera, and Sueca supply the rest. The main crops on this floodplain are orange trees, vegetables, and rice, which cover lands that were initially part of the Albufera Wetlands in Valencia and the old Corbera River (Carles et al. 2007).

In the second half of the twentieth century, the structure of the Jucar water system changed considerably. On the one hand, significant work was undertaken to regulate the river, with the construction of reservoirs in Alarcón (1957, 1,112 hm^3), Contreras (1973, 852 hm^3) and Tous (1993, 379 hm^3). On the other hand, the irrigated land in the basin also increased markedly, both in the section of the river in the Valencia region, where irrigated land peaked in 1998 at 64,550 ha, and also in Castilla-La Mancha, where a total of 90,000 ha were irrigated in the 1980s. The water plan for the basin established annual demand at 1,450 hm^3 in 1997, when total resources were estimated at 1,647 hm^3 a year. But changes in the amount of rainfall, runoff, and marked use of aquifers in the middle section of the river rendered these calculations unreal. No more than 1,200 hm^3 have been available on average over the last two decades.

In this situation of water coming under increasing pressure, droughts have acted as mechanisms to adjust the resources allocated to traditional irrigation. The graph attached hereto illustrates a marked decrease in the annual supply from the *Acequia Real del Jucar*, which has been staggered over the last four decades. After each period of drought, consumption does not return to the same level recorded in previous decades. As a result, the river flows that used to provide a strong guarantee of supply in the district have been used to either eliminate deficits or to meet the demands of other sectors in the basin.

What changes have irrigators made that have favored this remarkable decrease in the Jucar's contribution to traditional irrigation? In the first place, a change in crop trends has been observed over the last few years (Fig. 6.2). Irrigated land in the municipalities of the Acequia Real del Jucar decreased by 8.7 % (5,283 ha) over the period 1982–2006. The main change in farmland use was that arable land (down by 39.5 %, 9,386 ha) was replaced by woodland (up by 11.1 %, 4,103 ha). The downturn in arable crops can be mainly attributed to artichokes, corn, tomatoes, watermelons, and melons. In contrast, the most prominent crop, rice, which accounted for 58 % of arable land in 1982, only recorded a decrease of 7.9 % (1,089 ha) and represented 88.7 % of arable land in 2006. The droughts intensified these changes in the use of farmland, which became consolidated during the normal years that followed.

In the second place, irrigators have executed numerous projects to concrete irrigation channels. At the beginning of the period displayed by the graph, only the main channel and some secondary ditches had been concreted, but the work to concrete the entire network was carried out throughout the 1980s and the beginning of the 1990s. This reduced channel leakages remarkably.

The rice fields are responsible for the main savings in irrigation consumption. They are built on old dried-up wetlands that are practically flat and supplied by a double network of irrigation and drainage. A large number of these rice fields, the so-called 'tancats', are below the water level of the Albufera Lake, which means pumping stations are required to drain them. The rice is only harvested once, during the summer, and is mainly bound for the national market. Some of the most profitable years have coincided with Atlantic droughts that have made it impossible to grow rice in the marshes of the Guadalquivir River (Andalucía). In the case of the Jucar rice fields, despite the enormous amount of water this crop demands, farmers have never stopped growing it even during the worst droughts.

During the drought in 2005–2008, when river flows were reduced to half the level recorded 1994–1996, the water reutilization systems installed over the last decade made it possible to continue growing rice. The experience gained from the drought in 1994–1995 and the scenario of increasing pressure on the resource helped people to see the need to enhance the efficiency of rice field irrigation, which registered the highest unit consumption in the district. The first measures adopted were put into practice in Sueca, where the long parallel drainage channels

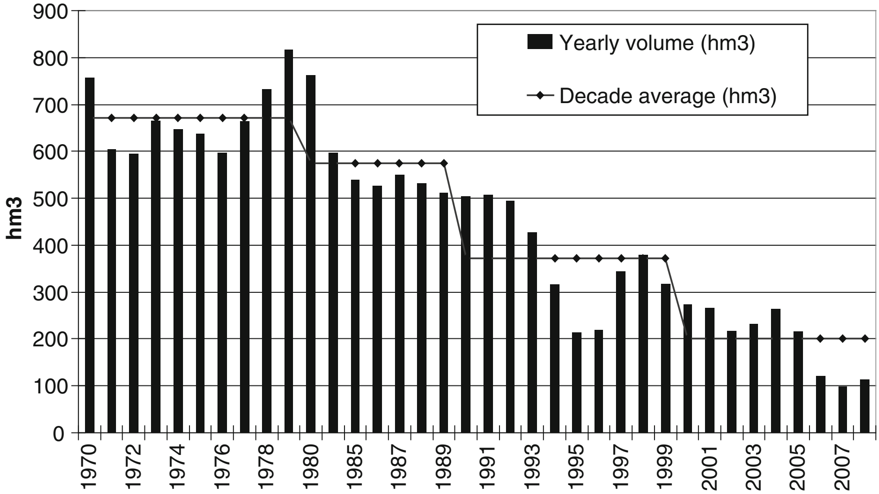

Fig. 6.2 Acequia Real del Júcar yearly uses (1970–2008). Data from river intake. No data available for 1982, 1983 and 1984 due to the destruction of infrastructures caused by the catastrophic flood of October 1982

and the flat landscape made it possible, after installing a pumping motor, to invert the flow of the water. As a result, the water that had reached the bottom end of the irrigation system could be reused at the top. The three reutilization stations in Sueca were joined by the irrigation association of Quatre Pobles and the Acequia Real in Sollana. As a result of these measures, it has been possible to grow rice using considerably less river flow than that available during previous droughts.

However, the decrease in the river flow extracted from the Jucar and recirculation of irrigation water has brought about changes in the salinity of the water that farmers have detected over the last few years. In the past, the rice fields on the land under the water level of the Albufera Lake, which floods them during winter, yielded the most. However, the situation today is different, as a result of intense recycling. Now, the rice fields on higher land, where such recirculation does not occur, produce the most. Moreover, a significant level of salt has been detected in a high percentage of pumping stations which, according to some authors (Gisbert et al. 2009), is the result of unprecedented marine saltwater intrusion.

This is not the only environmental impact caused by the decrease in surplus irrigation to the wetlands. During the 1990s, the urban and industrial areas in the basin improved sewage treatment, restoring some quality to the water in the lake, which had been in a hypereutrophic phase since 1974. In some years, during winter, there were several clear phases in which zooplankton bloomed briefly, reducing the algae and making the water transparent. These positive pulses have not been felt again during the first decade of the twenty-first century, as the progressive decrease in irrigation contributions is damaging the lake's ability to dilute nutrients and pollutants.

Finally, the most critical stages of droughts have been overcome by using underground water. These resources were only used frequently in certain sectors of the Acequia Real until the drought in 1994–1996. During this period, which irrigators remember as the most critical situation they had experienced up to that time, the agreement between communities of irrigators and the government authorized the creation of 72 wells, most of which were located above the detrital aquifer of the floodplain. The wells were opened in 1995 and worked at full capacity throughout the next season, the last of the drought.

Later, once the river reserves had recovered, these wells provided an average of 8 hm^3 to supply drinking water to the province of Alicante. The water from the wells has been used for traditional irrigation in the Jucar, and the same amount has been transferred from the head of the river to Alicante. Amortization and extraction costs were passed on to the new users. This procedure was suspended between 2005 and 2008, due to another drought that made it impossible to free this amount for users in Alicante and forced the use of the wells in the floodplain of the Jucar to cover irrigation needs.

6.6 The Riegos de Levante Margen Izquierda Irrigation District

The Irrigators Community Riegos de Levante on the left bank of Segura River (hereafter referred to as RLLB) has a total of 32,000 ha of irrigable land in the province of Alicante, from Albatera to El Campello, which makes it the largest irrigation organization in the region of Valencia. The organization, originally created as a private firm (1918), works today like a general community of users divided into nine base communities, which are in charge of distributing water to users. The general community distributes available river flows among the base communities in proportion with the theoretical surface area with irrigation rights in each. The association has three old government concessions (between 1918 and 1922) to manage 7.7 m^3/s, surplus water from the river accounted for 5.1 m^3/s and the surplus water of several secondary drainage canals. Moreover, in the 1970s, the government allocated 95 hm^3/year from the Tajo-Segura water transfer, although less than the amount initially agreed upon was received.

Today, the Irrigators Community RLLB irrigates a total of 26,000 ha and has 20,900 members. Figure 6.3 shows the volume of water that has been supplied over the period dating from 1975 to 2008 in cubic hectometres, both from the Tajo River-Segura River transfer and from the Segura River surplus water concessions held by the Irrigators Community. It must be said that the water obtained through the concessions is very low quality, due to having an extremely high level of salt (about 2,500 µS/cm). The average volume of water available over the last 34 years stands at 60.6 hm^3, which results in a total of 1,893 m^3 per hectare of irrigated land. This amount is clearly insufficient to provide irrigation for the vegetable gardens and orchards that are predominant in the area. However, over the last

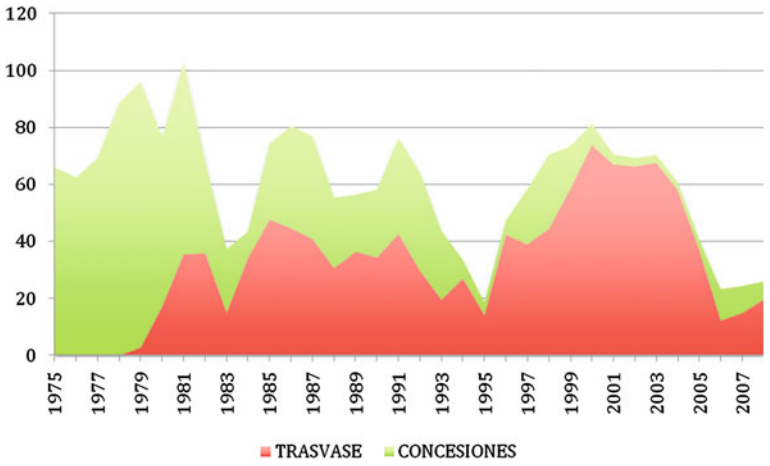

Fig. 6.3 Riegos de Levante yearly consumption (1975–2008)

10 years, the average has dropped to 53.9 hm^3, i.e. 1,684 m^3/ha. This shortage, which has become more pronounced over the last few years, particularly due to less water being received through the concessions, has meant the Irrigators Community and farmers have had to adapt their crops and techniques to this scarcity. During the droughts in 1983–1985 and 1995–1998, water resources diminished substantially, reaching allocations of 583 m^3/ha in 1995, without taking into account the water from other sources that will be mentioned later in this chapter.

The shortage of water in normal years has resulted in the total surface area of irrigated land decreasing and in changes in what the land is used for, with crops that need less water and are better adapted to the excess salt in the water being introduced. Statistical information on the surface area occupied by crops, at municipality level for the period 1982–2006 illustrates these trends. Generally speaking, total irrigated land used for arable crops in the municipalities under the jurisdiction of the RLLB has decreased by 40 %, whereas total irrigated land for tree growing has decreased somewhat less, by 30.4 %. Therefore, total surface area of irrigated land decreased by 33.3 % over the period in question. This significant decrease in irrigated land is due to farmland being converted into housing estates, infrastructures, etc. and changes from irrigated land to dry or fallow land.

Over this period, crops have changed from those less capable of tolerating poor-quality water to those that are more tolerant of saltier water. As a result, the land devoted to broccoli and grain increased in the 1982–2006 period from 44 and 1,379 ha to 1,557 and 1,983 ha, respectively. A decrease has also been observed in the crops that need the most water. For example, the land used to grow maize and alfalfa has halved (from 2,082 ha in 1982 to 740 ha in 2006), whereas the amount of land devoted to growing short-cycle vegetables (lettuce, escarole, etc.) with a

Table 6.1 Land use change in RLLB (%)

PERIOD	Change in arable land	Change in woodland	Total
1983–1985	−5.0	−3.7	−4.1
1995–1996 to 1997–1998	−57.8	−7.8	−19.0

lower risk of lacking water, has increased. In contrast, there has been an increase in the surface area devoted to crops that require very little water, such as cereals, with the exception of corn and rice, grain and date palms. All these crops have experienced increases in surface area, ranging from 25 to 53 %.

In this region, which suffers from a chronic shortage of water, the effects of a drought are much more devastating than in other areas studied. The droughts considered occurred in the periods 1983–1985 and from 1995–1996 to 1997–1998, during which time resources diminished substantially. Table 6.1 reveals that irrigators have adapted their crops as much as possible during these periods to minimize losses. The main strategy employed was to stop irrigating the arable land in order to guarantee irrigation for the woodland. Although the amount of woodland irrigated also decreased during the periods of drought, farmers stopped irrigating these types of crops, which are no longer considered irrigated crops, temporarily becoming dryland crops. This is particularly the case of almond trees and grapes, both of which are more suited to and cope better with a shortage of water.

In response to the shortage of water, the Irrigators Community increased the amount of available resources in 2008, using alternative sources as only 25.9 hm^3 could be obtained through the Segura River concessions and the Tajo River-Segura River transfer. In the first place, water was obtained from the wells used during droughts that are owned by the Confederación Hidrográfica del Segura. In addition to this, the Mancomunidad de Canales del Taibilla (state-run body that supplies municipalities in the province of Murcia and the north of Alicante) together with communities of irrigators in the area, purchased 30 hm^3 from the Estremera Irrigators Community, which belongs to the Tajo River basin, 5.4 hm^3 of which went to the Irrigators Community on the west bank of the Segura River. The community also had treated water, and is going to incorporate more from the coastal area in the next years (Alicante and Santa Pola), where tourist development provides an important amount of effluent during the summer. Taking into account all the foregoing sources, the community had a total of approximately 60 hm^3 of water in 2008.

The irrigation organization is currently in the midst of a modernization process financed by the state and the regional government. This process began in 1998, when the work towards improving and modernizing irrigation in the area was declared a common interest. A budget of 160 million euro was estimated, which amounts to slightly more than 6,000 €/ha.[6]

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[6] Land value between 60,000 and 100,000 €/ha and yield value between 7,000 and 10,000 €/ha, depending on crops variety.

Changes are also being made in the way irrigation is managed during droughts. The base communities take turns and, upon the request of a farmer and following payment, supply the hours he/she requires at 50 l/s. In the years when there have been sufficient resources, which have been few, demand is not restricted. However, in normal years limits are imposed depending on the resources available by establishing a maximum time and volume for each unit of land. Notwithstanding, farmers frequently swap or transfer turns during these periods (García-Mollá 2000).

6.7 Conclusions and Recommendations

Responses given to drought by irrigators' communities are determined by a wide range of factors—historical evolution, hydrological conditions, institutional framework, agrarian structures, etc.—which show an enormous spatial variability at local level in Mediterranean regions. This underlines the need for further research on the characterization of water users' associations' response to drought and water shortages in the region. Future work should involve building a regional matrix using a broader sample and multifactor analysis. This information could be extremely important to obtain greater insight into this topic and to feed models of management built by experts and used by public water organizations.

Some preliminary conclusions may be drawn from the analysis of the four case studies and some recommendations made. First, the strategies followed by the communities of irrigators to cope with drought and water shortages in the four case studies seemed to be strongly conditioned by the origin of water resources. For the two cases in which rivers are the main source of water, the reduction of the water supply by surface unit was higher than in areas with groundwater. In these districts, users respond by increasing water demand and, therefore, pressure on aquifers increases and piezometric water levels fall. Groundwater provides a better guarantee in this region, as has been stated by several authors when referring to previous droughts, but demands more sustainable management.

Obviously, in terms of changes of soil use and crops, the impact of drought was more severe in the areas irrigated with fluvial water and mainly where structural shortages were more pronounced. The case of Riegos de Levante, in which drought induced important changes in varieties and surfaces, illustrates this behavior. However, in the Vinalopó area, other long-term changes, partially linked to the search for greater economic efficiency of water, have been identified. The statistical series studied present occasional problems of inconsistency, a fact that reveals that the administration should make a better effort in soil use data collecting.

In general terms, recent droughts seem to have had a positive effect on several water users' associations in the region. According to the recent paradigm developed by the ISDR discussion group (2003), the irrigators and the administration have acted as a drought-resilient society. The 1994–1996 drought stimulated the incorporation of new sources of water and the search for greater efficiency. The opinions of irrigators demonstrate that this period has had a cathartic effect on irrigation management in the area and has helped to overcome the recent 2006–2008 drought.

The aim of this work was not to quantify vulnerability or the guarantee of supply in each of the four irrigation districts visited. However, by simply comparing their recent trends we can see how diversification of water resource supply is a suitable strategy to reduce the vulnerability of each irrigation area against droughts and water shortages, as is shown in Vinalopó and the lower Júcar cases. This work demonstrates that in a relatively small area in the Mediterranean, there are very different levels of vulnerability, generally related to the origin and diversity of resources and their supply guarantee. For this reason, actions such as the hydraulic interconnection of different basins or districts—for example to make it possible to recharge aquifers and permit interannual exchanges among users with different drought sequences—appears to be a recommendable future solution to reduce drought impacts. Therefore, a better description of irrigation districts and local responses to droughts would be the best starting point.

The incorporation of new water resources, in a context of growing pressure on water resource management, may only be a short-term solution. We have seen how resources obtained urgently during previous droughts—such as groundwater in the Jucar River, treated water in some Vinalopó communities, or gains generated by the increased efficiency through modernization programs—could in a few years be allocated to new users or assumed as regular resources, thereby losing their value as possible reserves or solutions for future emergencies.

Modernization plans and programs for irrigation infrastructures have become, without a doubt, the most important weapon to fight water shortages. In the last 25 years, 53.8 % of irrigated land in the Valencia region, approximately 179,000 ha, has abandoned traditional gravity irrigation practices in order to introduce drip irrigation techniques. Despite the fact that saving water is not a top priority for farmers, important water savings have been detected in several areas, such as the paradigmatic case of the Vall d'Uixó irrigation district. There, the rationalization and pressurization of the irrigation network, together with a better knowledge of crop necessities according to soil and plant properties, has reduced water consumption in plots by up to 70 %.

Water-saving plans and programs shouldn't be considered only on a local or agrarian scale. The reduction of water inputs in any irrigation area, particularly in traditional systems and old wetlands, could result in important damages to adjacent ecosystems. The case of the hypereutrophia of the Albufera Lake and the recently detected marine intrusion of the surrounding marshes, closely linked to the reduction of water inputs from the Jucar River, highlight the need for a more integrated approach to the design of this kind of program. Most of modernization plans implemented in Spain pay attention to water savings in the catchments, but not very often in the outputs of the irrigation system. The impacts detected in this case of study underline the necessity to adopt a more holistic approach in the improvement of irrigation efficiency and mitigation of water scarcity.

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Chapter 7
Crop Choices with Limiting Water Supplies: Deficit Irrigation and Sensitive Crop Growth Stages

Robert B. Hutmacher

Abstract Limited supplies of good-quality water in semi-arid and arid crop production regions often results in intense competition for water supplies among agricultural, municipal, and environmental interests. This increased competition can provide motivation for agricultural water users to reduce planted acreage, change practices or use equipment to control water losses, improve efficiencies of water application or irrigation scheduling, and consider changes in water management to impose some periods of deficit irrigation. Each of these choices has consequences for the crop, land and producer, the magnitude of which often depends on the knowledge of the agent making the choice as well as other factors outside of their control. For instance, if deficit irrigation is to be effective, it requires identification of growth stages sensitive to reduced water applications. Additionally, deficit irrigation requires development of new irrigation scheduling approaches that are based on a reduction of applications, at least during a large portion of the less-sensitive crop-growth stages. Crop species have different sensitivities to water deficit and, therefore, the potential impact on crop productivity (yield) will likewise be different. Crop-quality characteristics can also be adversely affected, some of which can impact marketability and the relative value of the crop. Objectives of this analysis are to describe crop and water management issues that can arise when deficit irrigation is considered as a water-saving approach. This chapter also provides examples of crop species characteristics that impact the suitability of deficit irrigation as a workable management option when irrigation water is scarce.

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7.1 Introduction

Water stress occurring with limited soil water availability can cause an array of physiological, morphological, and biochemical changes. Classical changes are increased solute concentration at the cellular level, reductions or loss of cell turgor, stomatal and non-stomatal reductions in photosynthetic activity, and changes in membrane permeability and structure (Chaves and Oliviera 2004; Bray et al. 2002). Studies over a range of plant species and even across genotypes have identified differences in their ability to maintain turgor and growth under water stress conditions by avoiding dehydration or through tolerance of dehydration. Some plants have been identified with differences in primary and lateral root density, differences in ability of roots to develop deep in the soil or through restrictive soil layers, and differing in root growth rates and ability to rapidly develop new roots in response to changes in soil water status following rain or irrigations (Jordan and Miller 1980; Taylor 1980). Many of these characteristics may be more important to plant survival during extreme drought stress and for the ability to recover and regain acceptable growth rates and reproduce successfully following stress. Other characteristics that confer higher photosynthetic productivity or improved production of harvestable product per unit of transpired water will be important in achieving acceptable plant productivity during more moderate drought stress, such as might be imposed when water is in limited supply in irrigated crop production.

The Central Valley agricultural production area of California, comprising the Sacramento Valley north of the delta region and the San Joaquin Valley south of the San Francisco Bay delta, has what is typically described as a Mediterranean type of climate. This type of climate is characterized by cool, wet winters (most rain between months of November and April) and essentially dry conditions with relatively little chance for significant rainfall the remainder of the year. Rainfall during the May through October period in most of these areas is sporadic and inadequate to meet significant portions of crop water requirements. In most of the inland crop production areas of California, rainfed crop production will not produce economically viable yields for most agronomic or horticultural crops. Winter rainfall can meet a significant amount of crop water needs for shorter-season winter crops, such as lettuce in some California crop production areas, but in California's inland Central Valley, growing season rainfall cannot be counted on to meet much of current crop evapotranspiration (ETc) needs for warm-season crops beyond beginning the season with some stored soil moisture. Under the high-input, high-production-cost conditions prevalent in current California production agriculture, mild to moderate water stress is the typical range of stress imposed during the growing season for most crops. This is because growers are usually not willing to subject irrigated crops to severe water deficits for any significant duration due to expected severe impacts on yields and/or quality. For what have typically been fully irrigated production fields, it can be argued that plant morphological or physiological characteristics that help produce sustained or at least moderately high productivity at mild to moderate drought stress may be much more useful than plant characteristics that improve survival under extreme, long-duration drought. Without any warm-season irrigation, the severity of plant water stress that typically would occur would produce uneconomical yields and quality problems for most crops currently grown in the Central Valley of California.

Cropping patterns in California are diverse, with more than 350 different crops grown within the boundaries of the state (California Department of Water Resources 2005, 2008). These crops include: (1) vegetable crops and specialty annual or biennial vegetable or fruit-producing crops; (2) orchard system crops; (3) vineyards and mixed berries; (4) field crops, including pasture, feed, other grain and fiber crops; and (5) ornamental and floriculture plants. Planted acreages of these crops vary widely by production area within the state and, to some extent, with market prices and year. Many California farms tend to be highly diversified, since a diverse crop mix can help spread economic risks and provide opportunities to investigate and develop new markets. This diversity also can make it difficult for agricultural producers or their staff to make decisions and identify the best irrigation management combinations to achieve crop production and quality targets when confronted with limited water supplies. To some extent, the long-term yield performance and profitability of some vegetable, fruit and nut crops in California have resulted in some substantial shifts in the mix of crops produced in many areas. An example of the types of shifts occurring is the change in percentage of irrigated acreage of field versus horticultural crops (here specified as mixed vegetable, orchard, and vineyard crops) from the late 1970s to early 1980s, versus early 2000s. During this period, total field crop irrigated acreage declined from about 7 million acres to just over 5 million acres, while total horticultural crop acreage increased by about 1.2 million acres (California Department of Water Resources 1983, 2005, 2008). These shifts were not always in response to lower water availability; indeed, in some cases, the shifts were in response to changes in the profitability per unit of applied water. Furthermore, some irrigated land went out of production due to land degradation from salinity or toxic trace element accumulations, and some other lands were lost to urban development.

When irrigation water supplies are limited, crop profitability may only be one of a number of factors influencing crop choice. This is because limited water supplies dictate a need for some flexibility in cropping choices to adjust to available water supplies covering a range of sources and water qualities. Irrigation of crops in the year 2000 was estimated to use about 80 % of the total developed water supplies (surface water plus groundwater pumping) in California (California Department of Water Resources 2005). With this in mind, it is not unexpected that many policy makers and residents expect that diversions of water from agriculture can and should represent a source of water when confronted with limited water supplies. Approaches will be needed to identify options and possible changes in practices to reduce total on-farm water use if dictated by water supplies, climatic conditions, increased demand from non-agricultural users, and regulatory actions. This chapter will provide a discussion of crop and water management issues that should be considered when deficit irrigation is evaluated as a water-saving approach. Examples of crop species characteristics with potential to impact deficit irrigation as a workable management option will also be provided.

7.2 Options for Improved Water Use Efficiency

Numerous studies have identified options for improving water use efficiency in agriculture in irrigated areas; options included:

- Improvements in irrigation delivery systems;
- Irrigation scheduling improvements to avoid deficits during periods of peak crop sensitivity;
- Irrigation scheduling and delivery amounts to better match crop water use and soil water storage capabilities/limits;
- Potential for use of deficit-irrigation practices, including water-savings potential, and the resulting impacts on yield, quality, and production problems.

Some of these changes can be relatively capital-intensive and costly to implement, such as conversion from surface irrigation to drip or microspray irrigation systems. These changes, though, may result in large water savings of potentially significant economic value, or allow producers to sustain a particular level of production and area cultivated while irrigating with less water. Other changes in practice, such as improved irrigation scheduling or attention to crop growth stages sensitive to water stress, may be somewhat less costly to implement. However, they require some period of learning and possibly more time committed to monitoring crop growth stages and levels of soil or plant water stress.

One significant change in irrigation management practice over the past 20 years in the western San Joaquin Valley is the large reduction in pre-plant irrigation amounts for many annual crops, such as cotton or processing tomatoes. In some of the heavy, clay loam soil areas of the western San Joaquin Valley, pre-plant irrigation amounts of 25 to 30 cm (10 to 12 inches) were not unusual two decades ago, or even more recently in some areas. These applications served to replenish soil water depleted by the prior crop and provide a fairly excessive leaching fraction. In more recent years, fields that are to be furrow-irrigated during much of the growing season have seen a change to hand-move sprinkler lines for pre-plant and even the first and second irrigation of the growing season. This has increased labor costs and sprinkler line acquisition and placement costs, but has made it possible for growers to greatly reduce early season water applications, if desired and warranted by soil and plant conditions. In some cases, this change to sprinklers and reduced-water applications has also provided greater uniformity of water applications during the early growing season, and reduced deep-percolation losses that have contributed to shallow groundwater accumulations and problems.

A significant factor contributing to the success of reducing pre-plant irrigation in the past is related to moderate to low salinity (0.3 to 0.7 dS/m electrical conductivity) of surface water irrigation supplies in multiple irrigation districts. This has produced more moderate rates of salt accumulation and less immediate need for larger leaching fractions. However, as irrigation water supplies have become less available and alternative water supplies (groundwater) of higher salinity are utilized, these and other management practices that provide reduced salt leaching can become more problematic. These changes in early season irrigation practices can be of general value in saving water and improving the efficiency of water use. There can be a negative consequence as well, including salt build up and potential damage to future crops associated with limited leaching. Restrictions in drainage water disposal options in many of these same western San Joaquin Valley irrigation districts also exacerbate the salt and trace element accumulation problems (Letey and Feng 2007).

The idea of employing deficit irrigation on some crops as part of an overall farm water management approach is that the deficit-irrigated crops will be subjected to reduced water applications and a degree of water stress, either through all growth stages or targeted during particular growth stages. Any negative yield or quality impacts with the deficit-irrigated crop(s) will be balanced against the value of necessary water savings or against the continued ability to fully irrigate some other crop(s) that are severely impacted by reduced water applications. For some crops such as cotton, seed crops (seed alfalfa), some grapes, and olives for olive oil production, yield or crop-quality improvements may be associated with plant water stress occurring at strategic times. A requirement for making deficit-irrigation practices work is detailed knowledge of crop responses to water stress, including available information on the relative sensitivity to water stress at different crop-growth stages.

7.3 Deficit-Irrigation Opportunities and Experiences

A large body of work in California and other arid and semi-arid regions over a period of many decades has described field research designed to assess crop water requirements under full irrigation. Irrigation system design calculations similarly assume that systems are designed to meet full irrigation water requirements at peak crop evapotranspiration (ETc) times of the production year. For many crops grown in California, there are good estimates of full ETc needs for the year, plus crop coefficients to estimate ETc at daily, weekly or monthly intervals for different production regions. The reality in many production regions of California in recent years, however, is that water supply limitations brought about by climatic variation, regulatory actions, and competition for limited supplies result in irrigation water allocations that often will not meet full ETc water requirements in many irrigation districts in the state. New water storage systems or transfer arrangements to make up the deficits are unlikely. Trends are that increasing populations and associated municipal and industrial needs will further constrict available water supplies, and the ability of different users to pay very different price structures will dictate available options. These factors will mean that some crops may be candidates for either reductions in acreage or for deficit-irrigation practices to reduce total on-farm water consumption.

Investigating the potential for deficit irrigation to be acceptable for any crop requires identification of growth stages sensitive to reduced water applications, and the development of new irrigation scheduling approaches to be used during less-sensitive crop growth stages. There also is a growing body of literature related to a type of deficit irrigation called "partial root zone drying" that will not be discussed here, but may have applications in some situations (Kang and Zhang 2004). A large body of research has been devoted to many production agriculture crops to identify crop characteristics such as:

- Plant growth stage sensitivity to water deficits, including impacts on current year versus future yields and harvestable product quality (Kirda et al. 1999);
- Impacts and specific sensitivity to the timing as well as severity of water deficits (Bray et al. 2002);
- Availability of genetic differences in types of sensitivity to water deficits, including both the timing and severity of deficits (Chaves and Oliveira 2004; Jordan and Miller 1980; Taylor 1980).

7.4 Crop Species Differences in Suitability to Practice Deficit Irrigation

Crop species have some basic, recognized differences in sensitivity to water deficits and the resulting potential for impacts on crop productivity (yield) as well as crop quality. Several detailed reviews of deficit-irrigation practices and research covering a broad range of crop responses to deficit irrigation are available (Fereres and Soriano 2007; Kirda et al. 1999; English 1990). Some specific crops grown widely in California can be used as examples to discuss potential for adaptability to improvements in water use efficiency with irrigation scheduling, as well as potential impacts of deficit irrigation on crop yields, quality, and value. Water shortages can pose serious constraints on all water users and, if severe enough, agricultural interests will be forced to make hard decisions regarding which crops require continued irrigations at non-limiting levels, versus those crops that might be better-suited for short- or longer-term deficit irrigation.

Predicting the consequences of different scenarios of reduced irrigations requires knowledge of drought-tolerance traits of each crop. In response to many types of stresses, including water deficits, plants can make adjustments in terms of phenology, morphology, and physiology, with responses related to a wide array of biochemical and physical changes occurring with certain stresses. Morphological and physiological traits with potential value for drought adaptation include drought escape, drought avoidance, and tolerance mechanisms. Some of these mechanism or combinations of mechanisms are better suited to survival under severe water deprivation and recovery after stress is relieved. Others may have more value for continued productivity under less-severe water-deficit conditions. The latter scenario is more likely of interest to California farmers, since successful use of such approaches would give them, at worst, modest reductions in crop yields, reductions in water use and costs, and perhaps the ability to redirect some irrigation water for more profitable crops or uses.

7.5 Irrigation Scheduling, Deficit Irrigation and Plant or Soil Water Status Indicators

On-farm weather stations capable of estimating reference evapotranspiration (ETo) are widely used in California. Both private farms and the California Department of Water Resources (DWR) integrated network of automated weather stations in the California Irrigation Management Information System (CIMIS) use these systems. The CIMIS website can be accessed via computer at DWR http://wwwcimis.water.ca.gov/cimis/welcome.jsp or University of California websites such as http://www.ipm.ucdavis.edu/WEATHER (California DWR 2005). With these weather stations and crop coefficients available from irrigation districts, the University of California and other sources, it is possible for producers to determine short-term estimates of crop evapotranspiration (ETc) for use in irrigation scheduling for full ETc replacement. Despite easy access to CIMIS ETo and weather data, and availability of soil and plant-based water status evaluation tools, USDA surveys typically indicate that less than 15 % of growers utilize these tools to make irrigation scheduling decisions (USDA 2003).

Under conditions in which growers want to practice deficit irrigation to stretch limited water supplies, differences in rooting depth and soil water storage occur, or shallow groundwater is potentially available to plants, plant or soil water status monitoring tools can provide supplementary information. These tools can assure that unnecessary water applications are limited and damaging levels of plant water stress avoided. The devices are particularly useful for timing irrigations, rather than quantifying the amount of water to apply, such as CIMIS described above. Examples of successful use of plant water status monitoring tools to provide useful irrigation scheduling supplemental information include stem water potential measurements using pressure chambers in numerous nut and fruit tree crops (Jones 2004). Additionally, the tools can affect mid-afternoon leaf or stem water potential (pressure chamber) and crop water stress index derived from canopy temperature measurements in cotton (Howell et al. 1984; Grimes and Yamada 1982). Growers and irrigation industry representatives have experience with a wide variety of soil water monitoring sensors used over many years in a wide range of crops. When properly placed, these soil sensors can also be of use in making adjustments in irrigation scheduling and in monitoring potential for soil water movement beyond the effective rooting zones.

7.6 Deficit-Irrigation Examples: Experiences with Select Annual Crops

Deficit-irrigation approaches have been developed by both researchers and growers with an understanding of the potential impacts of water stress at certain time periods on specific physiological processes important to growth. In the most detailed evaluations, attention has been directed toward key developmental processes, such as impacts on fruiting bud formation, pollination, or new shoot development important to future fruiting site formation. These efforts have provided agricultural producers with crop water management choices under water-limited conditions. A good level of understanding of growth stages or situations most suitable for deficit irrigation and potential impacts on yield and quality has been established for some crops; however, for other crops, more information is certainly needed. Descriptions of deficit-irrigation management discussions follow for specific crops.

7.6.1 Cotton (Gossypium Hirsutum L. and Gossypium Barbadense L.)

Cotton management regimes under full irrigation in California have typically involved irrigation scheduling that imposes mild to moderate plant water deficits that help manage vegetative growth rates and limit rank growth. Under water stress, cotton vegetative growth is reduced much more than its lint yield, thereby increasing the harvest index. In part the need for vegetative growth management was influenced by the vigor, growth habit, and relative indeterminacy of the cotton cultivars being grown. Flower bud and fruit losses that may occur with some types of insect damage or with unfavorable weather conditions can further complicate irrigation management plans. Extensive fruit loss will trigger unwanted and excess vegetative growth and vigor that may require either delayed irrigation and water stress or plant growth regulator applications to manage. Cotton growth stages considered least sensitive to soil and plant water deficits are early vegetative development (through about seven to eight main stem node stage), after peak flowering, and into the early boll-opening phase of development. Growth stages found most sensitive to moderate to severe plant water deficits in some studies include early flower bud (square) development through the early flowering stage, with later flowering and boll development periods intermediate in sensitivity (Hake et al. 1996; Hutmacher et al. 1995).

The development of growth stage-specific, threshold levels of mid-afternoon leaf water potentials for growers to use in irrigation scheduling (Grimes and Yamada 1982) represented a significant tool for California cotton growers. Since their research related threshold leaf water potentials to specific yield responses, growers could use leaf water potential measurements to improve scheduling of irrigations to avoid earlier-than-required irrigations as well as delays in irrigation, which could result in more severe water stress and damage to yield potential.

Similarly, Howell et al. (1984) and Hutmacher et al. (1995) demonstrated the utility of leaf water potential measurements and the Crop Water Stress Index approach, based on canopy temperature measurements, to assess levels of water stress associated with soil water depletion. Howell et al. (1984) demonstrated the utility of these approaches to assess plant stress associated with soil root zone salinity.

Hutmacher et al. (1995, 1998) reported that under subsurface drip irrigation in a deep clay loam soil, lint yields of both Acala and Pima types of cotton in San Joaquin Valley of California studies at irrigation levels of 80 % ETc applications from late squaring through two weeks past peak bloom were not significantly different from yields at 100 % ETc applications. This produced significantly higher water use efficiencies than plants in treatments receiving irrigation water at 100 % ETc during this same period. Similarly, Bhattarai et al. (2006) reported that cotton lint yields in Queensland, Australia, were similar in drip irrigation treatments that supplied 75, 90, or 105% of estimated daily crop ETc during the period from squaring through late bloom, resulting in significant improvements in water use efficiency at the lower water application rates. Under furrow irrigation, deficit-irrigation approaches in the western United States have concentrated on evaluations involving: (1) delays in applying the first within-season irrigation, with irrigation timing determined based on mid-day leaf water potential thresholds (Steger et al. 1998); and (2) extended irrigation frequencies that allow more soil water depletion and higher stress levels imposed prior to irrigations (Grimes and Yamada 1982), or elimination of some late-season irrigations after vegetative cutout (Munk et al. 1994). Under conditions with moderate to deep rooting depth, yields were maintained or reduced significantly less than ETc, and water applications were reduced with these furrow management schemes. Another factor with potential to impact deficit-irrigation options for cotton is the relatively high salt-tolerance noted for this crop. In comparing crops for suitability for salinized soils or for use of degraded irrigation water supplies, salt tolerance can influence water supply and water management options. While varietal differences in salt-tolerance are known to exist in cotton (Fowler 1986), efforts to incorporate this characteristic into modern commercially available cultivars have been limited.

7.6.2 Alfalfa (Medicago Sativa)

In a wide range of irrigation management studies, alfalfa yields within climatic zones have been found to be essentially linearly related to cumulative crop evapotranspiration (ETc) over the season (Grismer 2001). While crop yield can be impacted at any production location by other constraints to growth, such as insect pressure, soil aeration, or salinity issues, and periods of very low or very high temperatures, reductions in irrigation water that produce plant water deficits and reductions in ETc typically will also reduce yields. In evaluations of studies done across multiple production regions across California, Hanson et al. (2008a, b) identified a number of options for consideration under conditions of limited irrigation water supplies, including:

- Fully irrigate only part of the planted alfalfa acreage, and provide little or no irrigation water to the remaining acreage;
  - Irrigation is maintained to limit water deficits on portion of acreage in order to maximize yields per acre on that ground and maintain higher forage quality.
  - Remaining areas with very limited or no irrigation will suffer major reductions in yield if no major rainfall occurs.
  - Particularly in very hot desert production areas, plant losses can occur if duration of no irrigation period is too long.
- Fully irrigate for spring and early summer production, reduce or eliminate later irrigations;
  - Limits water deficit impacts on yield and quality of earlier harvests, which generally are better than late-season harvests in yield and quality under California conditions.
  - Reduction in irrigation or no irrigation late season will reduce yields, but usually has not been found to damage long-term plant survival if the duration of the dry period does not exceed several months (Hanson et al. 2008a), although this may not be true under very high summer temperature periods (>45 C) in desert production areas.
- Reduce the number of irrigations between cuttings or decrease applied water per irrigation to reduce total applied water;
  - Reductions in number of irrigations between cuttings can be achieved with surface irrigation methods. Water savings achieved by this method can be impacted by length of cutting cycle and soil type/soil water holding capacity.
  - Reductions in applied water per irrigation is not achievable with all irrigation methods. This approach is much more workable with sprinkler or drip irrigation than with furrow or flood irrigation, where the amount applied per irrigation is more a function of slope, water application rate and soil intake conditions.

In areas where irrigation water salinity levels add significantly to soil salt and trace element loading and rainfall is low, any of these reduced water application approaches also bring the eventual risk of salt-induced damage to stand survival and yields.

7.7 Deficit-Irrigation Examples: Experiences with Select Perennial Nut Crops

7.7.1 Pistachios (Pistacia Vera L.)

Pistachio deficit-irrigation management research conducted over a period of years by Goldhamer and Beede (2004) and described by Goldhamer (2005), indicated specific growth stages during which deficit irrigation and plant water deficits had greater potential to reduce crop yields or impact nut quality. Additionally, less-sensitive growth stages could be targeted if irrigation water supplies are limited. Their recommendations are matched to specific growth stages and phenological periods: Stage 1. bloom through shell expansion (April 1 to May 15 in the San Joaquin Valley (SJV) of California; Stage 2. shell hardening (May 16 to June 30 in the SJV); Stage 3. nut filling, shell split and hull slip (July 1 to Sept. 15 in the SJV); Harvest Period (Sept 16–30); and Postharvest Period (October 1 to November 15 in the SJV).

Deficit-irrigation periods identified for reduced water applications in their studies included: (1) 50 % reduction in applied water during Stage 2 (shell hardening) period; and (2) 75 % reduction in irrigation during the postharvest period. Conversely, periods their research identified as not suitable for deficit irrigation included: (1) Stage 1 (bloom to shell expansion) period; and (2) Stage 3 (nut filling to hull slip stage). Their research indicated that reductions in applied irrigation water according to these recommendations in the San Joaquin Valley of California could result in reductions in crop ETc from about 104.5 cm (41 inches) to less than 80.5 cm (32 inches), with relatively limited impacts on yield or nut quality at least over the short term (i.e., several years). There is less available data to indicate effects of many years of this reduced irrigation strategy on tree growth, and longer-term impacts if these approaches were imposed in a very low rainfall area while the tree canopies are still expanding.

When the trees are grown in winter rainfall/spring and summer dry conditions such as the San Joaquin Valley, with highly variable or very limited winter rainfall, their research also indicated the importance of assessing the degree to which fall irrigations and winter rains replenished root-zone soil water. If soil water conditions are limiting as the plants approach bloom, irrigations should be applied to limit damage from water deficits during this critical growth stage. Another important characteristic of pistachios that could have an impact on suitability of the crop for certain agricultural land and certain water supplies is the greater salinity and boron tolerance of pistachio trees in comparison with many vegetable crops or other tree crops.

7.7.2 Walnuts (Juglans Species, Juglans Regia L.)

Research in California on deficit-irrigation impacts on walnuts offers some interesting contrasts with similar research efforts described for pistachios. In research conducted over many years by Goldhamer et al. (1988, 1990), Lampinen et al. (2003), and Buchner et al. (2008), short-term and long-term impacts of deficit irrigation practices on walnut yield and quality components were investigated. The early season period, described as late-winter into early spring, is typified by March and April periods of fairly rapid root growth and activity, followed by leaf out in March and April for most commercial varieties. Male and female flower development is followed by pollination, typically completed by late April in the San Joaquin Valley of California, after which there is rapid expansion of the hull and immature nut of the fruit, as well as rapid shoot growth.

Typically, during June there is a shift from shoot development and fruit size to development of the shell and kernel, with kernel development progressing through late June into July and filling of the tissue continuing into September with major commercial varieties in the San Joaquin Valley. Water deficits during the post bloom period and into the summer months can decrease nut size, reduce shoot growth and new leaf development, if severe enough stress occurs (Lampinen et al. 2003; Goldhamer et al. 1988). Bud formation on new vegetative shoots can continue through the summer under favorable conditions, and significant water stress can impact fruiting site formation during subsequent seasons (Buchner et al. 2008; Goldhamer et al. 1990). Near the beginning of fall, in September, water stress during the hull split period has been associated with problems with hull tights, dark kernel color, with potential to negatively impact crop value (Lampinen et al. 2008). Mild deficit irrigation can be practiced post harvest in fall and winter months, provided it is not severe enough to lead to weak shoots prone to winter die-back.

Fairly extensive work on regulated deficit irrigation of walnuts has occurred in California in the San Joaquin and Sacramento valleys during the past two decades. The studies covered responses not only during the years of deficit irrigation but in subsequent years after full irrigation was resumed. Goldhamer et al. (1988, 1990) looked at hedgerow plantings of Chico walnuts, comparing fully irrigated walnuts to others irrigated at 33 and 66 % of full ETc levels throughout all crop growth stages. The first year of deficit irrigations largely reduced nut size with only minor impacts on in-shell yields. Additional years of deficit irrigation, however, reduced shoot growth, new fruit-bearing wood and fruit number to a greater extent. Over a three-year period of deficit irrigation, cumulative three-year totals for dry in-shell yield were about 20 and 40 % less than fully irrigated trees for the deficit irrigation treatment levels, respectively. Walnut size was reduced by water stress, and off-grade nut percentages increased, both of which reduced crop value. Upon reinstatement of irrigation at full ETc levels, shoot growth and new fruiting wood responded in previously deficit-irrigated trees, and within a one- to two-year period, depending on severity of stress, the number of nuts, and in-shell yields recovered to yield levels measured in fully-irrigated trees.

Additional, later regulated deficit irrigation trials conducted with the dominant commercial walnut variety, Chandler, were reported by Lampinen et al. (2003), (2008) and Buchner et al. (2008). The trials focused on regulated deficit irrigation in a younger (9- to 14-year-old trees) hedgerow orchard in Sacramento Valley, and an older (20- to 25-year-old trees) conventional orchard in the northern San Joaquin Valley. Deficit irrigations were avoided in these trials during early stages of tree and fruit development, with mild water deficit treatments (about 65 to 70 % of full ETc) and moderate water deficit treatments (50 % of full ETc) compared with full-irrigation treatments during the mid and late season growth stages. The younger orchard was more sensitive to deficit irrigation, with three-year cumulative dry in-shell yields reduced by 26 and 40 % in the mild and moderate deficit treatments, compared with the full-irrigation treatments. As noted in the earlier studies by Goldhamer et al. (1988, 1990), impacts of periods of deficit irrigation in the Sacramento Valley Chandler study on younger trees carried over even after full-irrigation levels were restored, with full-yield recovery taking one year in the milder deficit irrigation treatment and two years in the moderate treatment. In the older, conventional spaced Chandler orchard in the northern San Joaquin Valley, three-year cumulative effects of mild and moderate deficit-irrigation treatments reduced yields about 18 to 20 % in both treatments. Indications in these trials with larger, more widely-spaced trees are that more extensive roots reduced the impacts of deficit irrigation at those sites.

Overall, results of regulated deficit irrigation in walnuts point out the difficulties in developing a strategy for large reductions in water application that do not have significant potential to impact yields or quality beyond the first year the deficit irrigation is practiced. In established orchards, moderate deficit irrigation during mid-season and late, post-harvest reductions in applied water have been described by Buchner et al. (2008) and Lampinen et al. (2003, 2008) as having potential to save as much as 30 cm (12 inches) of applied water with only moderate impacts on current-year yield and nut quality, and less impact on shoot development important to the following year’s fruiting potential.

7.8 Other Factors Affecting Crop Choice

The crop examples used to describe deficit-irrigation responses and options were selected to demonstrate some of the differences major semi-arid zone crops have in relative sensitivity to deficit irrigation and impacts of available irrigation management options when confronted with water limitations. Examples reviewed are not meant to be all inclusive in representing the mix of crop responses to deficit irrigation growers should consider when making choices under water-short conditions. Deficit-irrigation research has been conducted in California and other semi-arid areas for many crops, including but not limited to other widely grown crops such as almonds (Goldhamer et al. 2006), processing tomatoes (Hanson and may 2004; Hanson 2008), peaches (Johnson and Phene 2008; Johnson et al. 1992), olives (Grattan et al. 2006; Beede and Goldhamer 2005); and wine grapes (Prichard et al. 2009, 2010). Individuals considering reduced irrigation options for these and other crops would be well advised to review crop-specific information on responses to different types of deficit-irrigation practices to assist in reducing negative impacts on yield and quality.

Deficit-irrigation strategies may sound relatively straight forward in terms of potential for direct impacts of reduced water applications on yields and quality. However, there can be additional factors to consider that may be less direct. Some factors with potential to influence crop choices and suitability of deficit irrigation plans include: (a) salinity and trace element composition of available water supplies; (b) resulting salt and toxic trace element accumulations in the root zone, and deficit-irrigation impacts on reductions in leaching fractions (amounts of applied water in excess of ETc) that can promote downward transport of these constituents; (c) potential for crops to make use of shallow groundwater, including groundwater supplies with degraded quality (salinity, trace elements, nitrates); (d) price of the crop and profit potential; (e) impacts of deficit irrigation on crop quality (improved with modest deficit irrigation in some crops; quality damaged in others particularly under more severe stress); (f) desirability of rotating crops for disease or pest control; (g) recent or significant investments in production, harvesting equipment or processing facilities for single crops or types of crops; and (h) fulfillment of long-standing contract requirements to produce specific crops.

The above examples include factors that impact incentives for change. Other economic factors, such as the reliance of certain industries that are dependent on reliable output of crops (such as energy crops for biofuel energy facilities, forage and other feed for dairies) can also be important influences on which crops are deemed suitable for deficit irrigation and which industries can best deal with possible reductions in total production.

7.9 Options, Issues and Opportunities

7.9.1 Improved Understanding of Salt Tolerance, Salinity Management Options

In many agricultural production regions in the semi-arid western United States, the perception and reality of tightening water supplies have resulted in reduced water applications for many crops and a greater likelihood that less water is applied to provide leaching of accumulating salts in the upper root zone. Even though irrigation water quality in many areas is relatively low to moderate in salinity (0.4 to 2 dS/m), long-term use of these irrigation waters in a high ETo environment will result in accumulations of salt and potential plant toxic trace elements within the root zone, unless moved by leaching via rainfall or water applications in excess of ETc (Hanson et al. 2008c). In situations for which water of even higher salinity is the only available water source, or irrigation water sources are blended with drainage water to extend water supplies (Rhoades 1983), the threat of salt and potentially plant-toxic element buildup (i.e., B and Cl) is a major and ongoing threat to productivity. Restrictions on disposal options for drainage water in watersheds and basins in many parts of the arid and semi-arid western United States, combined with limited water supplies available to use for leaching, will result in worsening situations with respect to managing salt for continued agricultural productivity. Deficit irrigation, if practiced repeatedly in water-limited areas, will have the effect of further concentrating salts within the root zone. Maas and Hoffman (1977), Rhoades (1983) and many others describe salinity management issues, crop species differences in tolerance of root zone salinity and trace elements, and relative impacts of soil salinity management on short- and longer-term crop yields.

Multiple studies identify crops, such as cotton, sugar beet, pistachio, barley and a few other commercial crops as having relatively high salt tolerance, at least at some growth stages (Bray et al. 2002; Fowler 1986; Maas and Hoffman 1977). It is likely that limited water availability will make renewed efforts to find improved salt tolerance an important undertaking. In areas with both limited irrigation water supplies and salinity problems, some crops are likely to be eliminated, as grower options and more salt-tolerant species may need to be shifted to more marginal soils if they are to remain in production. In semi-arid areas, such as the San Joaquin Valley of California, accumulations of salt and trace elements (e.g., boron) are not transient problems relieved each year by rainfall adequate for leaching below the root zone, but rather are developing and worsening problems. Without long-term solutions that involve some capacity for drainage water disposal, even identification of crop species or cultivars with improved salt and trace element tolerance will only represent a solution useful for a limited duration.

7.9.2 Crop Maturity Classes and Growing Season Length

When irrigation water is relatively inexpensive and fairly available, California producers of many annual crops can take advantage of a relatively long growing season, with a lot of available heat units to produce crops, and high-yield potentials due to the generally favorable climate for longer-season crops. Cultivars of some annual crops, such as cotton, developed for the California market reflect this in terms of being indeterminate in growth habit, with long-duration fruiting periods to aim for high yields. In addition, many of the crop and insect pest management schemes developed for cotton in the San Joaquin Valley and for Arizona were based on the approach that some early season fruit losses were allowable, since early losses could be compensated for with a lengthened fruiting period, and continued growth and fruit maturation time added at the closing end of the growing season. This approach, assumes that irrigation water supplies are adequate and affordable to extend the growing season, and that the value of the incremental yield added with that later fruit has a value significantly greater than the irrigation water cost. When water supplies are limited and/or more expensive, these assumptions may no longer be valid for some crops.

Attempts to reduce total seasonal water requirements by switching to earlier maturing varieties is one approach under consideration for some annual crops. However, identification of appropriate cultivars or cultivar characteristics may not be straightforward. There is some evidence for crops, such as cotton, that early maturing varieties can produce higher yields under a range of drought conditions (Namken 1973). Other research suggests that higher yielding cultivars under water-limiting conditions are not related to earliness and shorter season production (Bourland 1989; Cook and El Zik 1993). It should be noted that most of these types of studies have been done under conditions of climatic drought, in which the timing and relative intensity of the drought periods can be quite variable. In these instances, a high degree of reproductive flexibility or a very short period for harvestable product production can be beneficial. The situation in semi-arid areas with little or no rainfall in the production season and nearly full dependence upon irrigation may be different. Additional investigations into shorter-season production approaches and cultivars are likely to be of value for the water-limiting conditions in California, since the timing of our limited water periods may be at least partially under our control. In the marketplace, of course, cultivars and production methods developed involving shorter season production will only be workable if profitable yields and acceptable quality are produced.

7.9.3 Genetic Improvements

Genetic diversity in the response of crop plants to various types of drought or limited water availability has been a direct or indirect selection process through many years of conventional breeding. It is recognized that there are genetic differences in physiological responses to different timing and severities of drought. When identified, plants with improved productivity or survival potential under specific types of drought will have great potential to expand producer options under limited water conditions. Certainly in rainfed agriculture production areas, field varietal screening efforts in semi-arid and arid zones have identified better performing and poorly performing cultivars under different patterns, timing, and severity of water limitations. Drought stress impacts have generally been demonstrated by the level of yield reduction occurring relative to “potential yield” determined for non-stressed conditions; either produced by well-timed rainfall or by timely irrigations.

The degree to which any period of drought stress impacts yields is determined by factors including cultivar differences in sensitivity, but also by the timing of water limitations (relative to sensitive plant growth stages) and severity and duration of water deficits. Better performing plants under drought conditions are those that suffer relatively limited or at least lower yield reductions below potential yield under non-limited water availability. For plant breeding or selection work, the stability of relative yield performance (yield of a cultivar expressed as a percent of other tested cultivars) can be evaluated in varietal screenings. These are performed under a range of soil and cropping situations, and over time and exposure to different timing, severity and duration of drought conditions. One characteristic that some breeders and seed companies prefer is the "stability" of any given cultivar in performing better than most other tested cultivars across a range of years and locations of field evaluations. Particularly under rainfed conditions, this range of conditions provides an evaluation of whether or not there are unidentified drought-resistance mechanism(s) that are valuable in maintaining productivity.

There is a history of this type of selection and evaluation of yield stability under rainfed conditions. However, it can be hypothesized that in areas such as California where full-irrigation has in the past been economical and regularly practiced, evaluations of stability of yield under different types of drought stress have not been a priority. That situation likely will need to change for quite a few commodities under consideration for production in California, as water costs as well as availability are exerting a much stronger influence on workable irrigation practices for crop production in semi-arid zones.

7.10 Conclusions

With continuing pressure on limited water supplies in the semi-arid and arid western United States, a broad range of well-established crops, and continuing interest in alternative crops, it is expected that there will also be continuing incentives to develop information on options for reductions in crop water use. Deficit-irrigation practices are likely to play a part in developing farm-scale and regional options to deal with water shortages. To be adopted and successful even in water-short areas, alternative irrigation management practices will need to be based on evaluations of likely water savings, acceptable yield and quality impacts, and the utility of soil and plant water status monitoring tools to help with decisions regarding the extent and timing of deficits so as to reduce the possibility the deficits will be too severe. High-value crops and high production costs in California will make it all the more important for any deficit-irrigation management scheme to have safeguards and monitoring tools as part of the approach in order to give the growers improved chances to minimize risks and negative impacts of reduced water applications.

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Chapter 8
Drought Adaptation Measures and Risk Tolerance of Commercial, Small-Scale and Subsistence Maize Farmers in the Free State and North West Province of South Africa

W. Durand

Abstract South Africa has long been recognized as a country subjected to recurring droughts of varying spatial and temporal dimensions. White maize is the staple food of most of the South African population, particularly the poor. Sixty-nine percent of the total South African white maize production is produced in the Free State and Northwest provinces, mainly under dry-land cultivation. The variability of the South African climate, especially drought periods, impacts on the country's ability to produce maize in sufficient amounts to ensure food security. This chapter explores the differences between commercial, small-scale, and subsistence farmers' adaptation measures regarding their cultivation practices to avert the risk usually associated with the expected onset of the season and the intensity of the mid-summer drought. The financial risk tolerances of both sectors are evaluated, as are the costs various agricultural inputs have on a farmer's ability to cope with drought. In the case of small-scale and subsistence farmers, production capital is lost during a drought as it is used to buy food. The benefit of the shift from an impact-and-relief approach to a risk-reduction approach in the government drought management plan is examined with the objective of improving food security.

8.1 Introduction

Of the many crops grown in South Africa, maize (*Zea mays* L.) is the most important grain crop with a volume contribution of $\sim$84 %, compared to other grains produced in the 2007/2008 season (Agricultural Abstracts 2009).

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Approximately 90 % of maize is produced under dry land conditions, and the majority of these plantings (~70 %) are found in the Free State and North West Province (Fig. 8.1). The climate of the Free State and North West Province is semi-arid with average rainfall of 457 mm (CV[1] 22 %) and 514 (CV 22 %), respectively (Schulze and Lynch 2007) (Fig. 8.2). Ideally, 450–600 mm is required during the growing season for maize production (Du Plessis 2003). Sustained maize production is, however, dependent on favorable distribution of rainfall throughout the growing season, and maize can even be produced with annual precipitation <350 mm, if distributed favorably (Du Plessis 2003). The even distribution of rainfall is most critical, particularly during the flowering stage when soil water stress reduces yields more than during other growth phases.

Drought of varying extent is a regular occurrence in northwestern Free State and North West provinces (Thomas et al. 2007). Drought can be attributed to a combination of factors, such as shortage of rainfall, high temperatures, and low soil water content (Blignaut et al. 2009). A soil's physical and chemical characteristics, as influenced by different production practices, have a considerable influence on its water absorption and holding capacity after a rainfall event. Two of the severest droughts of the last century occurred in 1982/1983 and 1991/1992 (Richard et al. 2001) (Fig. 8.3). Droughts are expected to increase in both frequency and intensity as a result of climate change (Shewmake 2008), and variability in rainfall is one of the main causes of drought (Tyson and Preston-Whyte 2000; Vogel et al. 2000). Van Heerden et al. (1988) found a good correlation between ENSO events and drought and, according to Tyson and Preston-Whyte (2000), the El Niño phenomena may account for approximately 30 % in rainfall variability. However, not all drought events in South Africa can be explained by these teleconnections (Tyson and Preston-Whyte 2000; Vogel et al. 2000).

South African agriculture is of a dualistic nature. The well-developed commercial sector plants maize for the domestic and export markets. In the domestic market, about 40 % of the maize produced is used in the animal feed industry, 50 % is used in the maize milling industry, and 10 % is used for other processes, such as seed, wet milling, and brewing (Maize tariff working group 2005). The maize milling industry mainly caters to the South African consumer, who demands a pure white maize meal (Grouse et al. 2005). Milling companies are thus pressured to ensure adequate stocks of white maize. This is mainly sourced from local production, but is imported if local production does not meet the demand during drought years. The subsistence sector mainly plants maize for its own consumption, while the small-scale sector plants for its own consumption but often plants a larger area to sell a surplus for additional income (Kirsten and Van Zyl 1998). In relation to the commercial sector, the small-scale and subsistence agricultural sector is very small and only contributes 4 % to total national maize production. Table 8.1 presents the area and yield for the commercial and small-scale and subsistence farming sectors for the period 1997–2009 and total number of farming

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[1] CV-Coefficient of Variation.

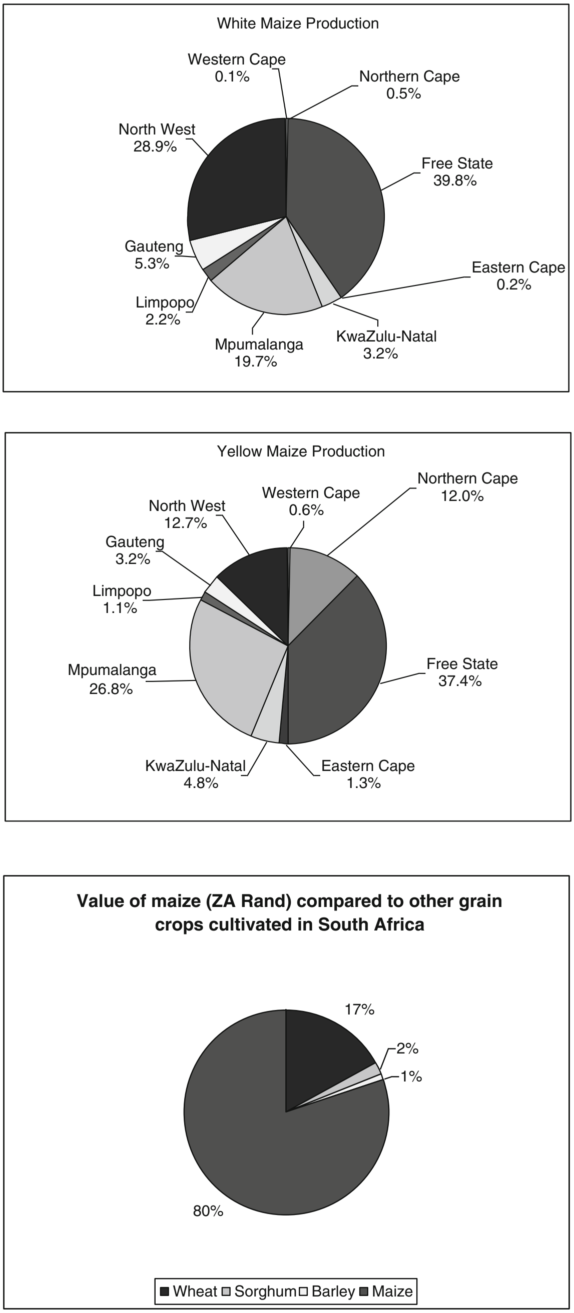

Fig. 8.1 Proportion of white and yellow maize production for the different provinces for the 2007/2008 commercial maize production season in South Africa (*Data source* CEC Media Release January 2009) and the value of maize (ZA Rand) in relation to the other grain crops cultivated in South Africa (Data source: Abstracts of Agricultural Statistics 2009)

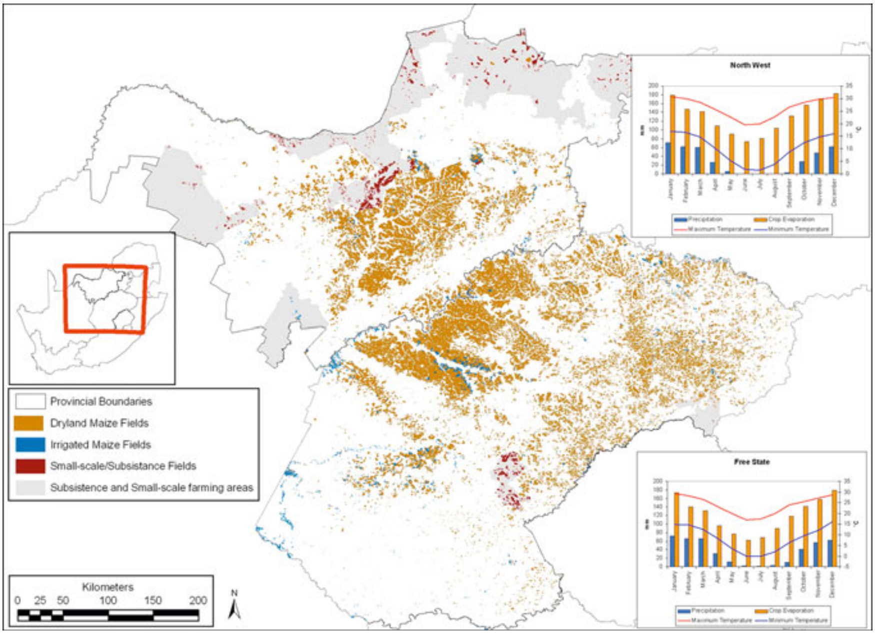

Fig. 8.2 Map of commercial maize fields and subsistence and small-scale farming areas in the Free State and North West Province with average monthly precipitation, crop evaporation (Penman–Monteith), minimum and maximum temperatures (*Source* Schulze 2007) for the two provinces

units found in the Free State and North West Province. In the Free State, small-scale and subsistence farmers contribute 0.5 % to the total area planted with maize; however, in the North West Province, this figure is 3 %.

Occurrence of drought in relation to the cropping calendar and the severity and duration of the drought has the greatest impact on maize production (Schulze 1984). The magnitude, duration, impact, frequency, and rapidity in onset of a drought all characterize the vulnerability of the maize farmers (Cutter 1996). Drought events often necessitate costly risk coping strategies. Within the South African dualistic maize farming system, these responses and mechanisms are different for the commercial and the small-scale and subsistence sectors. Commercial maize farmers have to absorb the income shock which leads to loss of physical capital, and subsistence agriculturists face the probability of poor nutrition in the future. The most important requirement for management of a sustainable farming enterprise is the ability to respond to, and develop, adaptation mechanisms to changes in the natural environment, such as an increased frequency of droughts. However, just as important are the responses and adaptations to the marketing environment.

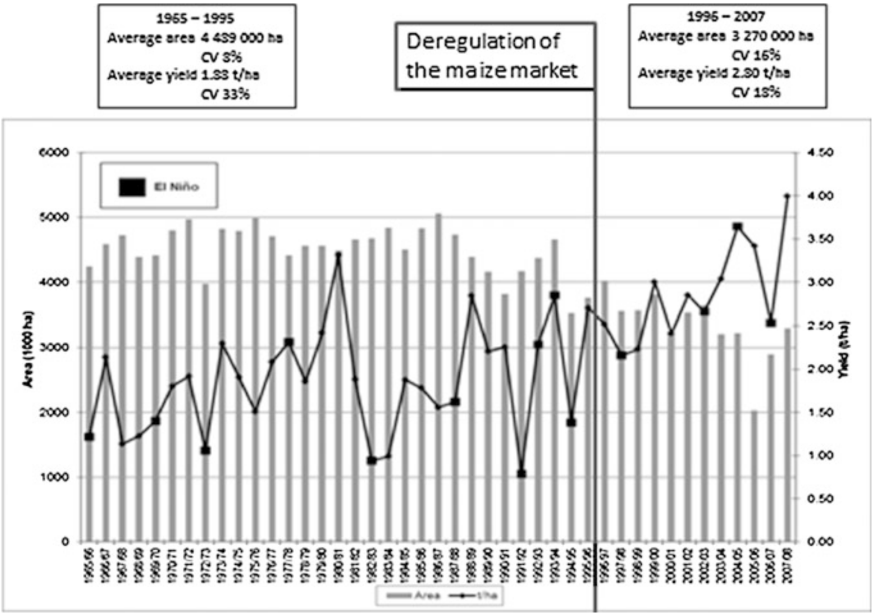

Fig. 8.3 National maize yields (t/ha) and area (1,000 ha) for the 1965/1966 to 2007/2008 seasons (*Data source* Abstracts of Agricultural Statistics 2009). Black blocks depict El Niño years (*Data source* ENSO-year classification after Australian Bureau of Meteorology 2009)

Table 8.1 Area and yield for the commercial and subsistence and small-scale farming sectors for the period 1997–2009 and total number of farming units found in the Free State and North West Province

Province	Farming type	Area[1]	Yield[1]	Experimental yield[2]	Number of farmers/ households
Free State	Commercial	1,032,000 ha CV 17 %	3.31 t/ha CV 20 %	5.38 t/ha	2002[3] 8,531 1996[4] 11,272
	Subsistence and Small-scale	5,200 ha CV 71 %	2.24 t/ha CV 24 %		32,400[5]
North West	Commercial	957,000 ha CV 23 %	2.67 t/ha CV 23 %	4.47 t/ha	2002[3] 5,349 1996[4] 7,512
	Subsistence and Small-scale	2,800 ha CV 23 %	1.15 t/ha CV 28 %		147,400[5]

[1] *Source* Agricultural Abstract 2009

[2] *Source* Maize Information Guide 2008

[3] *Source* Census of Agriculture 2002

[4] *Source* Agricultural Survey 1996

[5] *Source* Development Bank of Southern Africa 1991

8.2 Responses and Adaptations

8.2.1 Responses and Adaptations to the Natural Environment: Commercial Agriculture

One of the most important adaptation strategies that South African maize farmers employ to achieve maximum yields is to manage according to the yield potential of a field or area. The product of climate and soil can be regarded as the yield potential of a field or area. The yield potential can be determined by using average long-term yield data, because it reflects the inherent yield of the specific environment as well as the effect of agronomic practices, such as fertilization, soil cultivation, and plant population, as well as managerial abilities of a producer. To obtain a realistic yield target, all seasons (wet and dry) and even crop failures due to drought have to be considered. Setting a realistic yield target lowers the risk farmers take and increases their ability to produce economically.

Both climate and soil characteristics influence the potential soil water content (Hensley et al. 2006). Soil characteristics are largely influenced by tillage practices. Over the past decade in the Free State and North West Province a shift has taken place from conventional tillage practices to conservation tillage systems. These systems include no-till, reduced-till, and stubble-mulch cultivation systems. The advantage of these conservation tillage systems is increased soil water holding capacity, due to a higher organic matter content and reduced runoff (Lawrance and Berry 1999). During drought years, crops planted on soils managed using no-till deliver higher yields due to the better water-holding capacity and carry-over soil moisture from the previous season than those planted on fields using conventional tillage practices.

Crop rotation is also employed to reduce the risk in maize production systems. The yield and quality of maize is often better in a crop rotation system than under monoculture (Du Plessis and Botha 2007a, b). In the north western Free State and North West Province maize is rotated on an annual basis with soybeans, sorghum, sunflower, cultivated pasture, or left fallow (Loubser and Nel 2004). However, in a fallow system, no income is generated from the field, except for the short period it is used for grazing. The extent of this loss, especially during a drought year, must be weighed against the possibility of a greater financial loss, should the field have been planted and a poor yield obtained. A fallow field in which weeds have been effectively managed, which is then planted to maize in the next season, usually has a higher production potential even if rainfall is low (Botha 2007). Additionally, this field usually can be planted within its optimum planting window, and tillage requires less energy.

Management options employed to reduce the potential impact of drought are the use of well-adapted cultivars, together with optimum planting dates and densities in accordance with the outlook of the season (Pretorius and Human 1987). Commercial farmers in the Free State and North West Province usually plant maize varieties with a known production potential and yield reliability (Ma'ali 2008). New hybrids are usually phased in over time to make provision for genetic development. Commercial maize plantings in South Africa have followed the international trend with increased plantings of genetically modified (GM) maize that are mainly herbicide tolerant (notably Roundup) or insect resistant (notably stalkborer) in order to reduce the use of herbicides and pesticides and to decrease production costs. In the 2007/2008 production season, GM maize comprised 57.2 % or 1.6 million ha of the total area planted to maize. The GM plantings of white maize compared to the previous season increased by 48 % to 1,040 million ha, while yellow maize plantings increased by 7 % to 570,000 ha in 2007/2008 (Trends in Agriculture 2008).

Temperature and the onset of the rainy season usually determine the planting window of farmers in the Free State and North West Province. Farmers reduce their risk by planting within a planting window and using cultivars with different growth season lengths. That ensures that anthesis, during which the maize plant is most vulnerable to water stress, does not coincide with the mid-summer drought, which usually is expected from mid-December to mid-January. Secondly, farmers also reduce their risk by spreading the planting dates from 21 November until 11 December (Du Toit 1999). A medium season cultivar has been proven to produce the most stable yields in these regions.

In relation to other parts of the world, the commercial maize farmers in the Free State and North West Province plant at low-planting densities of 10,000–40,000 plants per hectare and row spacings ranging from 0.75 to 2.8 meters under dry-land conditions (Du Toit et al. 1994). This practice ensures water conservation. To compensate for the low planting density and wider row spacing, farmers choose cultivars with a high prolificacy, which have the capacity to produce a higher than average yield during wet years by producing two to three ears per plant (Du Toit and Prinsloo 2000).

In the Free State and North West Province, about 6 % of the total maize area is irrigated. Given the three times higher production potential of maize under irrigation, the contribution of irrigated maize to the total maize production is significant. Over the past 10 years, South Africa produced 131 % of its white maize and 116 % of its yellow maize requirement (de Villiers 2009). If this current irrigated area is not cultivated, due to drought, South Africa might not be able to produce enough maize to be self sufficient.

8.2.2 Responses and Adaptations to the Natural Environment: Small-Scale and Subsistence Agriculture

Determining the yield potential for small-scale and subsistence farmers is quite difficult. "Green mealies" (immature maize) are consumed early in the season, and most households buy additional maize meal from supermarkets and local shops, because they have insufficient quality or quantity of maize meal to feed their families between harvests (Gouse et al. 2005).

The small-scale and subsistence farming sector is more vulnerable to drought, as most of these areas are located in regions that are sub-optimal for crop production due to poor soils and erratic climate. In experimental trials, the arid area of the Free State (mean annual precipitation <550 mm) with climate and soils similar to some of the small-scale and subsistence farming locations of the two provinces, Bennie et al. (1994) have found that between 60 and 85 % of rainfall evaporates from the soil surface before making any contribution to production. Two systems have been identified that can be used by small-scale and subsistence farmers to effectively reduce run-off and evapotranspiration. The first is intercropping. Many authors reported that cereal-legume intercropping systems have much higher productivity than sole cropping systems (Austin and Marais 1987). This is attributed to reduced soil temperature and retained soil water. Intercropping is often referred to as live mulching. An additional advantage of intercropping is increased nutritional value and efficient use of space and labor (Mukhala et al. 1999). Secondly, if rainwater is harvested and channeled to an arable land in a dry area, the risk for crop production with variable rainfall can be reduced (Woyessa et al. 2006). Hensley et al. (2000) developed an in-field rainwater harvesting technique (IRWH), whereby runoff is captured in a no-till type of micro-catchment, which is covered with mulch. With the use of the IRWH technique, runoff and soil loss from the cropland were reduced to zero (Hensley et al. 2000). Using the IRWH technique, average long-term maize yields were significantly higher than those of conventional soil tillage production techniques (Tsubo and Walker 2007; Zere et al. 2007). Botha et al. (2003) found using organic mulch in the basins and stones in the run-off strips resulted in the lowest evaporation loss from the soil. Using IRWH in very low rainfall areas and poor soils, there is a 70 % probability that yields can increase from 1 ton per hectare under conventional tillage to 1.8 ton per hectare (Denison and Wotshela 2009).

The area planted to maize in the small-scale and subsistence farming sector depends on previous successes, particularly the previous season and rainfall indications at planting time. A series of drought years may negatively impact on the potential area planted to maize in a following good season as the resource base of the substance or small-scale farmer is low. Varieties planted are mainly of the open-pollinated type with a seed cost of about a quarter of that of the traditional commercial hybrids. Seed is also collected from the previous year's harvest (Tothova and Meyers 2006). Drought and low nitrogen-tolerant maize is currently been developed by the ARC-GCI[2] in collaboration with CIMMYT[3] through participatory evaluation projects (Derera et al. 2008; Bänziger et al. 2000), in the form of so-called mother-baby trials. Mother trials are researcher managed, while the baby trials are planted by smallholder farmers living near the mother trial sites. Using this technique, smallholder farmers are introduced to different drought-tolerant maize varieties and are empowered to choose the best cultivars for their production needs, according to their preferences.

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[2] ARC-GCI—Agricultural Research Council-Grain Crops Institute.

[3] CIMMYT—International Maize and Wheat Improvement Centre.

8.2.3 Responses and Adaptations to the Marketing Environment: Commercial Agriculture

A considerable change has taken place in the marketing system of South African maize over the past years to which all maize farmers had to respond and adapt. At the end of April 1995, the single-channel fixed-price system for maize was repealed and the Marketing of Agricultural Products Act, passed in 1996. Since then, maize has been traded in a free market in which prices are set according to forces of supply and demand (NAMC 2003). Before this, the maize market surpluses or shortfalls were covered by marketing schemes, such as the Maize Board, and government assumed responsibility for all imports and exports. The fixed-price schemes governed by the Maize Board guaranteed a fixed price to farmers as well as consumers.

In the new free-market system, the South African Futures Exchange (SAFEX) sets the benchmark for prices that traders can ask for, or offer, in the daily trading of maize. A number of factors related supply and demand have an effect on “futures prices.” In the short term, this is the seasonal climate outlook which is particularly influenced by any indications of an imminent drought. Long-term factors include technology, government policy, trade agreements, and changes in consumer preferences (Trends in Agriculture 2003, 2004). Production costs have increased considerably since 2005, making it more and more difficult for farmers to be profitable (NAMC 2007, 2008a). South African commercial maize farmers are, however, still very effective at producing maize under adverse climatic conditions and are efficient at keeping production costs down to acceptable levels (Blom 2007).

The area under maize has declined from more than 5 million hectares in 1986/1987 to 3 million hectares in 2007/2008 (Fig. 8.2). Additionally, a 17 % decline has occurred in the number of productive farming units from 1993 to 2002 in the Free State and 29 % in the North West Province (Agricultural Abstracts 2009). The decline in area can be attributed to farmers converting cropland to grazing to avoid the higher risk of production costs, especially of fields that are marginal due to soil and climatic factors (Groenewald and Nieuwoudt 2003). The decline in the number of farming units can be attributed to less successful farmers abandoning maize cultivation because of high debts and no additional credit for production in a following season. This results in the maize farming industry being more concentrated where large commercial farms dominate. A further loss of each of these production units due to drought and economic reasons may negatively impact food security as fewer farms will have to produce enough maize for an ever-increasing population.

With the free market system, maize farmers are exposed to international competition in that maize farmers in some countries are highly subsidized (Chabane 2002). Currently, South African maize farmers receive no government subsidy or any other form of direct financial aid. Farmers are therefore more and more subjected to what can be called an economic drought.

8.2.4 Responses and Adaptations to the Marketing Environment: Small-Scale and Subsistence Agriculture

The risk tolerance of the small-scale and subsistence sector is quite low and is exaggerated by drought, subjecting this farming sector to so-called socio-economic drought or famine droughts. The price of maize in the informal maize trade varies considerably. Farmers usually negotiate a better local price for their grain, compared to selling it in the formal market. However, small-scale farmers could benefit from the domestic market, provided they produce quality products (Makhura et al. 2001). Many small-scale farmers are unable to adjust to policy and market changes within the open domestic market and have had to leave the industry. This has a negative impact on government's objective of growing a black commercial farming sector (Chabane 2004).

For small-scale and subsistence farmers, the value of maize is much higher when expressed in terms of maize meal. As rural households can mill their own maize by hand or through a local miller, it is more cost effective for them to keep and mill the harvested maize than to sell the grain and purchase the meal (Gouse et al. 2005). Some small-scale farmers are able to produce a surplus that is sold directly to others in the community or to a local shop (Gouse et al. 2005). The monetary value of increased yield can be quantified in two ways: first, income generated by selling extra grain, and second, cost saving from not having to purchase maize meal. Food prices in South Africa rose by 15.7 % for the period January 2007 to January 2008, and the prices of a 5 kg bag of super and special maize meal increased by 22.29 and 28.00 %, respectively (NAMC 2008b). For the period January 2008–2009, the price of maize products increased by 8.59 % from the previous year (NAMAC 2009); however, for the period January 2009–2010, the price of maize products in the urban areas decreased by −1.43 % from the previous year but increased by 6.94 % in the rural areas (NAMAC 2010). The compounding of price has the consequence that poor households in rural and urban areas often spend more than 50 % of their income to buy basic food (Watkinson and Makgetla 2002). This has a significant impact on the small-scale and subsistence farmers because, in dry years, much of the production capital is lost in order to buy food.

Small-scale and subsistence farmers have indicated that land preparation, seed and fertilizer are the most costly inputs. However, when animal-drawn implements and conservation tillage are used, only fertilizer is the major expenditure (Dimes and Carberry 2007). In rural areas where family labor is available, weeds are mostly controlled by hand; however, small-scale farmers are increasingly using herbicides due to labor shortage and adoption of conservation tillage (Walker and Schulze 2006). The much higher seed cost of commercial hybrids and the eight-times higher price of genetically modified maize seed has limited the adoption rate of these varieties by small-scale farmers (Gouse et al. 2005). The main challenges for the establishment and development of a growing small-scale and subsistence farming sector are lack of access to land, financial services, mentorship programs, and markets (Van der Westhuizen 2005).

8.3 Other Possible Responses and Adaptations

The difference between livestock farming and maize cropping is that in a dry year the livestock farmers have the option to move their livestock to better pastures or sell off excess stock, reducing their risk. The planted maize in a field is, however, not a moveable asset and, in addition, maize can only be sold at the end of the production season once the grain has matured and can be harvested. Once planted, very few mechanisms are available to maize farmers to reduce risk. The most effective mechanism is to insure the crop by transferring the risk to the insurer. Hence, maize farmers have to endure drought unlike livestock farmers who can evade drought (O'Farrell et al. 2009). If maize production ceases to be economically feasible, growers who wish to remain on their farms will have to switch to either more drought-tolerant crops to livestock grazing, or branch out to game farming or the eco-tourism trade. Subsistence farmers who wish to keep producing food for their own consumption will have to switch from maize, which was originally introduced to Africa by the European settlers, to more traditional crops such as sorghum, millet, and cassava, which are more drought resistant.

8.4 Observations on Political Economy

8.4.1 Food Security

Food security can be defined by the availability of food and is the responsibility of the free market. The second leg of food security—affordability—is, however, the responsibility of government. Government must provide a policy environment whereby competition will drive down prices, economic growth and job creation will provide a means to buy food and a social safety network that assists those in distress. Affordability also requires infrastructure provision and maintenance by government to ensure proper support systems to the market (De Villiers 2009). It has been established that more than 60 % of the price of maize meal is attributed to transport, handling, milling, and retail costs (IRIN 2008). Affordability of maize as staple food for the nation has come under criticism lately due to the huge price hikes experienced both locally and internationally. The projection is that maize prices will continue to climb, due to rising input costs such as oil and fertilizer, increasing global demand, and a decrease in projected maize production due to future increased occurrences of droughts in the main production areas. The South African government has established a food price monitoring initiative under the supervision of the National Agricultural Marketing Council (NAMAC) that reports on changes in food prices on a quarterly basis (NAMC 2008b, 2009, 2010).

Food self-sufficiency on the other hand has to do with surplus production. As mentioned, the self-sufficiency index for white maize over the past 10 years has been 131 % and for yellow maize 116 % (De Villiers 2009). Food sovereignty is, however, a new concept that has to be taken into consideration by government and requires intervention. This is the right of people to define their own food and agricultural policies tailor made for their own unique circumstances (economically, culturally, socially, and ecologically) (De Villiers 2009). Food security and nutrition security are necessary, but not sufficient, conditions for food sovereignty. A food sovereignty approach comprises a number of different principles, ranging from market policies, food safety, food quality, the environment, the use of genetically modified organisms, transparency of information, and corporate accountability (Via Campesina 2001). The South African government must, through implementation of policies and institutionalizing food production and farmer support programs (National Treasury 2003), play a major role in creating an environment that is beneficial to the development and growth of the maize production industry to improve food security but also to promote food sovereignty. Given the current scenarios for South Africa attributed to climate change (Du Toit et al. 1999), in which temperatures will increase and rainfall will decrease and become more erratic, the cost for the South African government will increase if food sovereignty in terms of maize wants to be retained.

8.4.2 Government Drought Policy and Interventions

Drought management in the agricultural sector of South Africa has traditionally been the jurisdiction of the Department of Agriculture, Forestry and Fisheries (O'Meagher et al. 1998). In the past, government aid required magisterial districts (counties) to be declared drought stricken before receiving drought disaster status. This legal requirement necessitated a quantitative index that could be uniformly applied. This index was broadly defined as two consecutive seasons experiencing less than 70% of the average rainfall. Normal drought, for which a farmer was expected to be self-reliant, was of a period of one year and less. Using the index, some districts in South Africa were declared drought stricken more than 70 % of the time over a 30-year period, while other areas were never declared (Bruwer 1990). In some cases, farmers even became dependent on government aid. Using this kind of quantitative index a trigger is, however, biased, as the index, dependent on the deviation from mean annual rainfall, is skewed by the distribution of annual totals in the drier and more variable rainfall areas.

For many decades, the focus of drought management was on a phased-relief approach assisting mainly livestock farmers. However, after the 1980s, this scheme was modified to include a conservation ethos (Smith 1993). Once a drought was declared, conservation-minded farmers had to reduce their stocking rate to one-third, and a rebate on transport cost of stock feed was granted. Some of these schemes are still in operation in limited form (Monnik 2000). The 1991/1992 drought, however, witnessed a change in this relief perspective that included an attempt to incorporate a strong development component as well as a focus on managing vulnerability to drought. Table 8.2 summarizes drought investigations, commissions and policy agreements from 1992 to 2005.

The White Paper on Agriculture (South Africa 1996) and the White Paper on Disaster Management (South Africa 1999) provide some of the legislative framework on which the Drought Management Plan (DMP) for South Africa is based (South Africa 2005). The DMP proposes the development of a risk management system of which the features are prevention or reduction of disasters, mitigation, preparedness, response and rehabilitation, and guides interventions related to drought (Van Zyl 2006). The department of provincial and local government is responsible for the execution of the Disaster Management Act 57 of 2002. Drought management is the responsibility of national, provincial and local governments, farming communities, the private sector, and civil society. It is, however, felt that the present disaster aid for drought is not particularly suited to the needs of the maize farming community, either commercial and sustainable or small-scale, as these assistance schemes do not cover insured or insurable assets such as infrastructure and crops. For commercial maize farmers, this means they are self responsible for incorrect investment, financing, marketing, and production decisions. The current assistance schemes proposed in the DMP are only vaguely described and are not designed to replace what farmers have lost, but rather to enable farmers to continue production in a coming season through financial assistance.

8.4.3 Drought Mitigation Strategies in South Africa

Drought mitigation as outlined in the DMP aims to protect resources and community livelihoods. Its basic components are awareness, avoidance, early warning, and rehabilitation (South Africa 2005). People must be educated in order to create awareness. Avoidance involves the application of practices that reduce risk exposure in drought-prone areas, while the farmers' state of preparedness to drought is improved by early warning systems providing information on imminent droughts.

8.5 Awareness

An effective way to convey information would be for the government to work with the news media in reporting critical plans before and during a drought. It has been shown that commercial agriculture has been responsive to the news media (Klopper and Baartman 2003). However, high levels of illiteracy among subsistence farmers make the conveying of information difficult (Vogel 2000). Land

Table 8.2 Drought investigations, commissions and policy agreements from 1992 to 2005

Years	Investigations/commissions/policy	Issues	Reference
June 1992	National Consultative Forum on Drought (NCFD)	Coordinate a response to the then current drought crisis in South Africa	Vogel et al. (2000)
1993	Drought action coordinating centre	Submit a drought management proposal	National Drought Management Strategy (1993)
1995	National Disaster Management Committee (NDMC)	Drought management at national level	Vogel et al. (2000)
1997	Committee	The management of disasters including ENSO impacts	Vogel et al. (2000)
1997	Green paper on disaster management	Disaster Management	South Africa (1997)
1999	White Paper on disaster management	Reducing the vulnerability of the poor, enhancing community self-reliance in disaster management and a disaster management funding system to be used for the prevention and recovery phase.	South Africa (1999)
2001	Disaster Management Bill	Government's disaster management Bill for South Africa as set out in the white paper	South Africa (2001)
2002	Disaster Management Act	Legislative framework on disaster management in South Africa	South Africa (2002)
2005	National Disaster Risk Management Framework (NDRMF)	Legislative framework	South Africa (2005)
2005	Drought Management Plan (DMP)	Legislative framework	South Africa (2005)

Care projects have been found to be beneficial to drought management as they ensure sustainable resource management and promote the conservation of natural resources (Land Care 1999).

8.6 Avoidance

Avoidance involves the application of practices that reduce risky farming systems. Avoidance, however, also requires prior information to the main price determining factors, such as the size of the local production areas (planted area versus harvested area), the expected yield, and how it might be influenced by future weather, the size of the crop to reach the market, and the current stock levels (De Villiers and Jooste 1999). The National Crop Estimates Committee is responsible for releasing official, unbiased forecasts of the areas planted and production of maize, while information on producer deliveries, imports, exports, and consumption is administered by the South African Grain Information Service (SA-GIS), a section 21 Company, funded by the maize industry.

8.7 Early Warning Systems

Droughts are well suited to early warning systems because the disaster has a slow onset. In South Africa, due to the complexity of rainfall regime, the beginning but also the end of a drought is difficult to define, even when a variety of data is available (Monnik 2000). In South Africa, a number of seasonal forecasting products are available from a range of scientific, academic, and meteorological institutions (Johnston et al. 2004) and is disseminated through the media, Internet, and private consultants (Walker et al. 2001). The commercial agriculture industry has traditionally had greater access to seasonal climate forecasts than the small-scale and subsistence farming sector. Seasonal forecasts have been shown to be useful as an adaptive strategy to respond to climate variability, and are used by farmers to determine planting and harvesting dates, in-season tactical decision making and response to variability in market demand (Ziervogel et al. 2005). The South African Weather Service is responsible for drought assessment and keeping the agricultural organizations, news media, and public constantly updated on the latest developments.

Physical indicators of drought are the primary constituents of early warning systems. These indicators can be divided between meteorological and biological systems. Meteorological indicators used in South Africa are decile rainfall, the Water Satisfaction Index (WSI), NOAA NDVI[4] and the Standardized Precipitation Index (SPI) (Rouault and Richard 2003). The South African Weather Service provides long-lead forecasts and ENSO[5] advisories for use in Southern Africa. Biological systems include the ZA-Model, the PUTU-Veld production model, and Free State Agricultural Conditions (De Jager et al. 1998). Some of the products are under development, some are given routinely, and others, such as most biological systems that require more extensive work to compile, are only produced on demand.

The usefulness of early warning systems is dependent on the timely release of information and also on the correct interpretation of the specific conditions. For

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[4] NOAA-NDVI—National Oceanic and Atmospheric Administration's Normalized Difference Vegetation Index.

[5] ENSO—El Niño-Southern Oscillation.

example, farmers during the 1991/1992 and 1994/1995 seasons did not change their planting strategy, due to the slow release of climate information (Klopper and Bartman 2003). On the other hand, during the 1997/1998 season, the news media issued wide-spread warnings according to a survey by Klopper and Bartman (2003). In this event, commercial farmers modified their production decisions as a result of the seasonal forecast of an ENSO event that had previously had a negative influence on maize yields, due to drought conditions. However, the expected severe drought did not materialize. One reason was that there was a surplus of available surface water and the soil water content carried over from the previous season was still high. In 1998, forecasts predicted above-average rainfall for South Africa early in 1999, based on La Niña observations, however, the observed rainfall in the season was substantially below average (Blench 1999). This often leads to confusion among farmers. Increased forecast accuracy and resolution would improve the forecast utility for users. The amount of public interest and understanding of ENSO (Dilley 2003) has improved over the years and farmers now better understand and apply seasonal climate information (Klopper and Bartman 2003).

8.8 Rehabilitation

According to the DMP, national, provincial, and local government must financially contribute to post-disaster recovery and rehabilitation when a disaster such as a drought occurs. Any financial assistance provided must be in accordance with the national disaster management framework and any policy of the relevant level of government (Disaster Management Act 57 of 2002). Reciprocation is, however, an important feature of the DMP. This is the commitment made by communities to implement good conservation measures and sound farming practices to mitigate the impact of drought before they can access drought assistance.

8.9 Conclusions and Recommendations

Our need to understand both the natural and social responses to drought is made all the more important by the fact that the frequency and severity of droughts are expected to increase in response to anthropogenic climate change. Monnik (2000) has indicated the main constraints to future development and access of drought early warning systems as: first, a lack of a completed drought policy framework; second, a lack of coordination between institutions that do provide some type of drought early warning; third, a lack of vulnerability data bases; and finally, a lack of social indicators to form part of a holistic early warning system.

A clear policy framework is necessary, because it provides the foundation on which further systems development and integration between institutions can occur.

The first steps towards this goal are set out in the current DMP. However, this plan still has to be fully implemented. As already pointed out by Vogel (1994), the speedy implementation of a DMP is often hindered by the fact that in good years drought issues usually recede from the agenda.

As most of white maize as staple food is produced in the marginal regions of the Free State and North West Province, any succession of dry years will have a far-reaching influence on food security, not only by lower deliveries but also through the loss of productive farming units. Commercial maize farmers want relief from high-input costs, as they have reached the point that they are not any longer able to absorb the high-input costs. Farmers feel that the government is more focused on protecting consumers from high prices than on helping the producers. The commercial maize production industry wants government first to spend more on agricultural research to find methods that will lessen the impact of drought and, second, to set up drought insurance schemes (Van Zyl 2006).

History, especially the 1991/1992 drought, has indicated shortcomings in the drought policy, for instance, insufficient and untargeted assistance to the rural poor and farm workers (South Africa 1997). Calls were made for improved early warning systems, based on criteria for both physical and social vulnerability such as nutritional indicators and measures of vegetation change. Nutritional indicators are necessary, as the purchasing power of the rural population during a drought decreases because the price of maize meal increases. A reduction in earnings for the poorest households compounds the problem (Eldridge 2002). Government could investigate a poverty alleviation grant for subsistence farmers, based on average annual income and grain prices to enable households' access to food. Small-scale agricultural production should be made a central strategy for production so that households receiving the grant can buy food from local farmers, thus promoting local economic growth (Food Pricing Monitoring Committee 2003). The relief interventions should aim to limit the decreases in vulnerable communities' purchasing power and incomes that are generally associated with food crises during droughts (Eldridge 2002). To address vegetation indicators, Du Pisani (1987) advocated the CERES-maize model as a potential tool for drought assessment within the maize production sector. The crop-specific drought index for maize would enable policy makers to have an objective measure to declare areas "drought stricken" and to implement subsidy schemes on a fair basis.

Development of an effective drought early warning system is, however, particularly hindered by the absence of an adequate rain-gauge network and a coordinated climate database. Daily rainfall has, historically, been recorded at approximately 12,000 stations in southern Africa (Lynch 2004). There has, however, been a steady decline in the number of rainfall stations since the 1960s. Up to the year 2001, these rainfall data were collated, quality controlled, and disseminated by the Computing Centre for Water Research (CCWR). With the closure of the CCWR, no common point of rainfall data access is currently available. A network of rain gauges across a region or country should be designed to be sufficiently adequate to represent the spatial variability of the rainfall within that region (Schulze 2007). The Free State and North West Province are areas in which much of the rain falls in summer in the form of convective storms; therefore, close rain-gauge spacing would be best suited. The South African rain-gauge network is far from adequate to capture the spatial and temporal variability in rainfall, thus making it far from adequate to optimally sustain an early warning system (Schulze 2007). There are also very few stations in some semiarid regions of the country and sometimes none in the formerly independent homelands (Vogel et al. 2000).

For the South African commercial, small-scale and subsistence maize farmer, the speedy implementation of the DMP plan and the development of a coordinated easily accessible early warning system is of utmost importance. Their risk tolerance to adverse conditions such as a prolonged drought is low due to incurred financial constraints. Government assistance and intervention should not only reach the small-scale and subsistence farming sectors, but also be conclusive of the commercial farming sector. Although this sector has well adapted to the environmental constraints associated with droughts, its low financial risk tolerance due to high-input cost and competitiveness in a highly subsidized global market makes it vulnerable. Each maize farmer who changes his farming practice from maize to pasture or another non-maize producing system makes a large impact on the nation's food security and self sufficiency. A deficit in the availability of maize in the domestic market increases the maize price and often necessitates costly imports. Food prices subsequently increase, which affects above all the urban poor. It is thus recommended that, parallel to the development of a socio-economic index for subsistence farmers, an economic risk tolerance index should be developed for the commercial maize farming sector to aid policy makers, agriculturalists, and business. It should also assess the vulnerability of the sector to ensure equitable support in all drought relief efforts.

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Part II
Ecological Impacts of Drought

Chapter 9
Impacts of Water Scarcity and Drought on Iberian Aquatic Ecosystems

Carles Ibáñez and Nuno Caiola

Abstract The climate of most of the Iberian Peninsula (Spain and Portugal) is Mediterranean and undergoes cyclical droughts. Climate change in this region will likely exacerbate the frequency and span of droughts. The historical development of irrigation and the recent economic development put additional pressure on the scarce freshwater resources. Consequently, most of the rivers, lakes, estuaries, and wetlands are impacted by the reduction and regularization of the flow regime and overexploitation of aquifers, especially in the south and on the Mediterranean coast. The main responses of Iberian aquatic ecosystems to increased water stress are reported to be: changes in biotic community structure, changes in habitat availability, alteration of ecosystem metabolism, increase of eurytolerant and invasive species, increase of pollution, and reduced resilience against global change impacts. One of the main measures to be implemented for mitigating the effects of water scarcity in Mediterranean aquatic ecosystems is the establishment of a proper environmental flow regime. Future research should focus on quantifying the ecological effects of water scarcity and the role of environmental flows in maintaining ecosystem structure and function.

9.1 Introduction

From a management perspective, water scarcity is the shortage of water resources relative to water demands. Water scarcity is related to the absence of rainfall, but also to other non-meteorological factors, such as lack of infrastructure for water

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storage or transport, excess of demands or their mutual incompatibility, and constraints for water management (Martín-Carrasco and Garrote 2007).

Moreover, the Mediterranean region is expected to be greatly impacted by climate change (Ibáñez 2010), which will likely exacerbate the frequency and span of droughts. Climate change projections over the Mediterranean region, based on the most recent and comprehensive ensembles of global and regional climate change simulations, show a robust and consistent pattern, consisting of a pronounced decrease in precipitation, especially during the summer season. Interannual variability is projected to increase during summer, which, along with the mean warming, would lead to a greater occurrence of extremely high temperature events (Giorgi and Lionello 2008).

The historical development of irrigation and the recent economic development of Spain and Portugal put additional pressure on the scarce freshwater resources. Consequently, most of the rivers, lakes, estuaries, and wetlands are impacted by the reduction and regularization of the flow regime and overexploitation of aquifers (Suso and Llamas 1993; Ibáñez and Prat 2003; Chícharo and Chícharo 2006), especially in the south and on the Mediterranean coast of the Iberian Peninsula. The climatic variability and water use in the last decades produced one of the driest periods of the twentieth century of southeastern Spain, which provoked a marked decrease in river flows. A study of the last decades (Martín-Rosales et al. 2007) showed that precipitation fell by 9.2 and 11.7 % in Granada and Almeria, respectively, between 1980 and 1989. The decline between 1990 and 1999 was generalized in the region, and the year-to-year variability increased by 37–49 %. This variation was most pronounced in the rivers, three of which showed a reduced mean monthly flow of the order of 34 % over the period 1980–2003, in comparison to the decade 1969–1979. The most noticeable impact in the southeastern part of Spain over the last 40 years has been the intensive exploitation of groundwater. This has brought about a general decline in groundwater levels, drying out of springs, and leading to abandonment of numerous wells and boreholes, and higher salinity of soils and water.

Extended droughts predicted as a consequence of climate change (lower rainfall and higher temperatures) combined with human-induced changes to the natural hydrological regime will lead to reductions in the amount of water available for environmental and anthropogenic uses. Consequently, we may consider the effects of drought on aquatic ecosystems in a context of increasing water scarcity and variability due to growing human needs and to climate change. The ecological theory predicts that rapid and large changes in ecosystem structure and function will occur more frequently in the future as a consequence of chronic alterations from global change. In combination with other human impacts and natural disturbances, these changes will increase the rate of nonlinear changes and decrease ecosystem resilience (Smith et al. 2009; Scheffer et al. 2001). In this sense, most of the freshwater ecosystems are particularly vulnerable, due to the intensity and frequency of natural and human-induced disturbances; although, the Mediterranean species have life strategies adapted to resist drought periods.

9.2 Responses and Adaptations of Aquatic Ecosystems to Water Scarcity

Biota that inhabit hydrologically dynamic aquatic systems must possess morphological, physiological and/or behavioral adaptations to survive in highly variable environments (Humphries and Baldwin 2003). While drought can severely impact natural aquatic ecosystems, its effects have been and are exacerbated by direct and indirect anthropogenic modifications to streams and their catchments. Drought impacts in flowing waters are better understood than those in standing waters. However, knowledge of the ecology of droughts in flowing waters is scattered and fragmentary, with much of the available information being gathered opportunistically (Lake 2003). In streams, the major impacts are the loss of water and habitat availability, and the reduction of connectivity (Bond et al. 2008), as well as changes in water quality and salinity (Nilsson and Malm Renöfält 2008; Nielsen et al. 2003). In lakes and wetlands, the major impacts are loss of water level and flooded surface, increased mineralization of water and loss of biodiversity.

The main responses of Iberian aquatic ecosystems to drought and increased water stress are reported to be: changes in biotic community structure, changes in habitat availability, alteration of ecosystem metabolism, increase of eurytolerant and invasive species, increase of pollution and reduced resilience against global change impacts (Bonada et al. 2007; Gascón et al. 2007; Magalhães et al. 2007; Sánchez-Castillo et al. 2008). In the next sections, the responses and adaptations of the different types of Iberian aquatic ecosystems (rivers, estuaries, wetlands, and lakes) to water stress are analyzed.

9.2.1 Responses and Adaptations of Rivers

The flow regime is regarded by many aquatic ecologists to be the key driver of river and wetland ecosystems. Altering flow regimes affects aquatic biodiversity in a number of ways (Table 9.1). Increasingly, human water demands reduce the discharge of rivers and can influence the onset and duration of low flows during dry periods when agricultural and other needs are greatest (Agnew et al. 2000; Baron et al. 2002; Arthington et al. 2006). Furthermore, the frequency and duration of periods of water scarcity are predicted to increase in response to climate change and rising populations (Richter et al. 2003).

The human responses to drought-related water scarcity imply development schemes that cause severe water stress, which is known to be a major selective force in structuring aquatic habitats. Such schemes often imply the construction of dams that can produce substantial alterations to the flow regime, especially on flood magnitude and monthly flow pattern (Batalla et al. 2004). The dam-induced hydrologic changes affect channel morphology, sediment transport, and river ecology.

Table 9.1 Guiding principles about the influence of flow regimes on aquatic biodiversity, as formulated by Bunn and Arthington (2002)

Principle 1	Flow is a major determinant of physical habitat in streams, which in turn is a major determinant of biotic composition.
Principle 2	Aquatic species have evolved life history strategies primarily in direct response to the natural flow regimes.
Principle 3	Maintenance of natural patterns of longitudinal and lateral connectivity is essential to the viability of populations of many riverine species.
Principle 4	The invasion and success of exotic and introduced species in rivers is facilitated by the alteration of flow regimes.

In general terms, suitable habitat and refugia may be severely reduced or eliminated for periods ranging from hours to years (Magoulick and Kobza 2003; Magalhães et al. 2007). The drying process shrinks the water column, which reduces flow permanence and water quality, slows water velocity, transforming lotic into lentic habitats, and disturbs substrata composition. Consequently, these hydromorphological impacts alter aquatic and riparian vegetation (species composition and abundance), food resources and strength and structure of interspecific interactions (Stanley et al. 1997; Magoulick and Kobza 2003; Lake 2003; Davey and Kelly 2007).

Intermittent rivers are abundant in the Mediterranean region. They are characterized by unpredictable and high year-to-year variability in precipitation, resulting in lengthy periods of low water flows and devastating floods. In the Iberian Peninsula, these river types are under increasing pressure, due to increasing water uses, which affect water quantity and biodiversity. Human interventions include impoundment of rivers and alterations of channel morphology, mainly for irrigation and flood prevention.

Although in recent years the water quality of many Iberian rivers improved considerably, mostly due to the construction of wastewater treatment plants (Ibáñez et al. 2008), the overall ecosystem health of rivers decreased due to water quantity issues, especially in the Mediterranean streams. Therefore, the use of assessment systems exclusively based on physical-chemical indicators has become obsolete. Thus, to assess a river ecosystem, a great variety of parameters reflecting its structure and functioning resulting from different types of disturbance should be used (Karr et al. 1986; Allan 1995). Recently, it has become increasingly common to use multiple groups of organisms in bioassessment (Johnson et al. 2006), and this is one of the innovative aspects of the Water Framework Directive (WFD) legislation of the European Union (Ibáñez et al. 2010). In this holistic approach to assess the ecological status of rivers, the organisms used as biological indicators are regarded as ecological-based variables that respond to environmental conditions. Therefore, any disturbance in the functionality or structure of the riverine habitat, among them the hydromorphological ones caused by drought and water scarcity, will be reflected by responses in the functional structure of the biological communities.

Two of the most widely used biological indicators in river biomonitoring programs are the benthic macroinvertebrates and the fish fauna. In this section, we will present some of the responses of both assemblages to drought and water scarcity, with special emphasis on the fish fauna. Due to the biological features of fish, they are good indicators of impacts caused by water stress. Some of these characteristics are that fish live permanently in water; occupy a wide range of ecological niches; operate over a variety of spatial scales; have high longevity; developed complex migration patterns, making them sensitive to the presence of dams and weirs; occupy high trophic levels, integrating disturbances that affect lower trophic levels; and have more charisma than other species groups and provide valuable economic resources, being important to public awareness (Ibáñez et al. 2010).

9.2.2 Responses and Adaptation of Macroinvertebrate and Fish Assemblages

Species can be regarded as occupying positions in a multidimensional space (or niche) whose axes are defined by life history traits (Caiola et al. 2001; Caiola 2006). These traits shape “behaviors” for dealing with different kinds of environments (Wootton 1992; Villa-Gispert and Moreno-Amich 2002; Magalhães et al. 2003). Therefore, the ability of a species to adapt to changing or new environments will depend on its adaptive plasticity determined by its ecological strategy (e.g., reproduction, feeding strategy, etc).

One of the main habitat alterations caused by drought affecting benthic macroinvertebrates is the flow permanence. The responses of macroinvertebrate communities to flow permanence have been widely reported. The main response is a change in the assemblage species’ composition and structure (Fig. 9.1). A study performed in some Iberian streams exposed to increased water stress clearly demonstrated that droughts alter habitat availability, especially riffle-pool sequences causing important constraints in macroinvertebrate community structure (Bonada et al. 2007). In this study, it is shown that, although the observed habitat alterations do not cause changes in species composition, there are differences in the resilience and proportion of species with different ecological guilds when comparing stream systems with different drought impacts. In more intermittent systems, taxa with pool-like strategies dominate, while highly impacted streams are characterized by fauna with life-history adaptations to floods and droughts (reproduction by eggs or asexual, aquatic passive dispersal, resistance forms, tegument respiration, etc.).

A review of 50 papers (Matthews and Marsh-Matthews 2003) found that the most frequently demonstrated effects of drought on fish were population declines, loss of habitat, changes in the community, negative effects from changes in water quality, movement within catchments, and crowding of fish in reduced microhabitats. Thirteen other less-frequent effects also were identified (see Fig. 9.2).

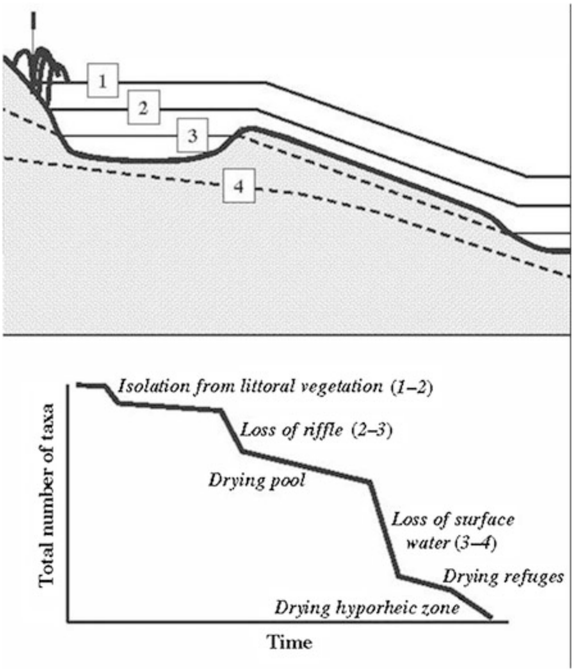

Fig. 9.1 Changes in macroinvertebrate assemblage composition in a "stepped" fashion during transitions across threshold discharges or water levels (*Source* Boulton 2003). During drying, total numbers of taxa are posited to decline sharply when submerged or trailing littoral vegetation is isolated from the free water (*1*–*2*), then as flow ceases in the riffle (*2*–*3*), and when surface water disappears (*3*–*4*). Plausibly, further declines occur in the hyporheic zone as subsurface water levels fall

The severe events of water scarcity commonly cause reductions in population size and species richness, especially of native and intolerant species (Magoulick 2000; Lake 2003; Magalhães et al. 2007). Negative effects on reproduction, condition and growth of individual fish have also been reported (Magoulick and Kobza 2003; Keaton et al. 2005). Moreover, these profound modifications in the aquatic ecosystems of the Iberian Peninsula directly threaten the native fish fauna and favor the invasion of non-native species (Elvira 1995, 1998; Moyle 1995). Numerous local observations prove that these human disturbances have negative effects on the local fish communities, especially on those species unable to cope with these changes due to their low ability to adapt to the new environmental conditions (Belliard et al. 1999; Anderson and Thompson 2004).

As a consequence of long-term geographical isolation, climate and fluvial regime, the Iberian native fish fauna is poor and highly endemic, with life history strategies adapted to extreme conditions (Doadrio 1989; Almaça 1995; Caiola et al. 2001; Caiola 2006). Therefore, understanding the effects of extreme droughts is particularly important in these systems (Blanco and González 1992; Cowx and Collares-Pereira 2000; Caiola 2006). However, many Iberian aquatic fish species seem to be already at the limit of their tolerance to increased frequency of extreme drought events (e.g., Cowx and Collares-Pereira 2000; Smith and Darwall 2006).

As shown in Benejam et al. (2010), the fish community structure of an Iberian stream highly impacted by water scarcity and drought suffered a significant decline. The observed decline was correlated with the water abstraction intensity.

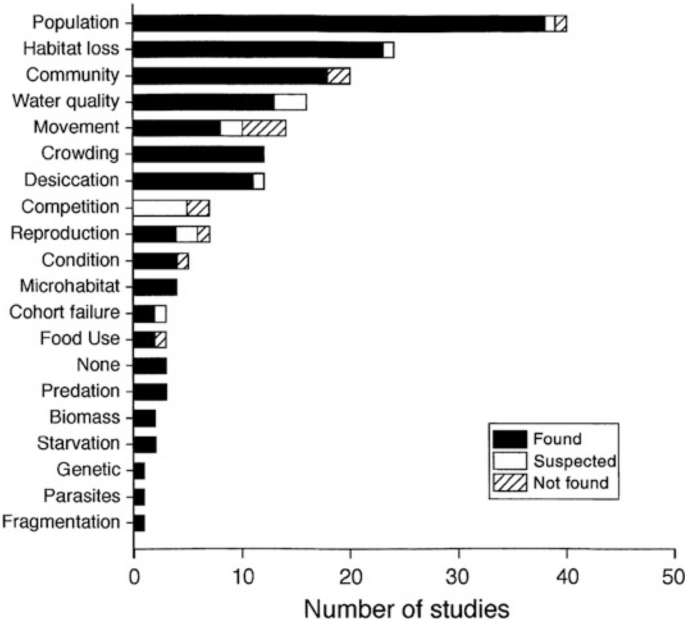

Fig. 9.2 Numbers of studies showing specified effects of drought on fishes, summarized from 50 previously published papers (*Source* Matthews and Marsh-Matthews 2003). *Solid bar* effect found by original authors or accepted as valid; *open bar* speculative or unconfirmed; *hatched bar* effect tested for but did not found significant by original authors

Assemblage features affected by drought were a decline in the total fish abundance, the reduction of the number of benthic species, and an increase in the number and proportion of intolerant species.

Another clear example regarding the impact of artificial water flow reduction over fish assemblages' structure can be found in the lower Ebro River (northeastern Iberian Peninsula). In this river stretch, the fish community is dominated by introduced species, and a significant relationship between flow reduction and dominance of invasive fish species has been found (Caiola and Ibáñez, unpublished data). In this study, it has also been possible to establish a critical water velocity threshold (water velocity directly depends on river flow) from which native species become dominant (Fig. 9.3). This is a highly valuable result regarding environmental flows management in the lower Ebro River that could also be extrapolated to other rivers with similar characteristics.

9.2.3 Responses and Adaptations of Estuaries

The responses and adaptations of estuarine ecosystems to drought and water scarcity are not well known in the Iberian Peninsula. Most of the estuaries have not

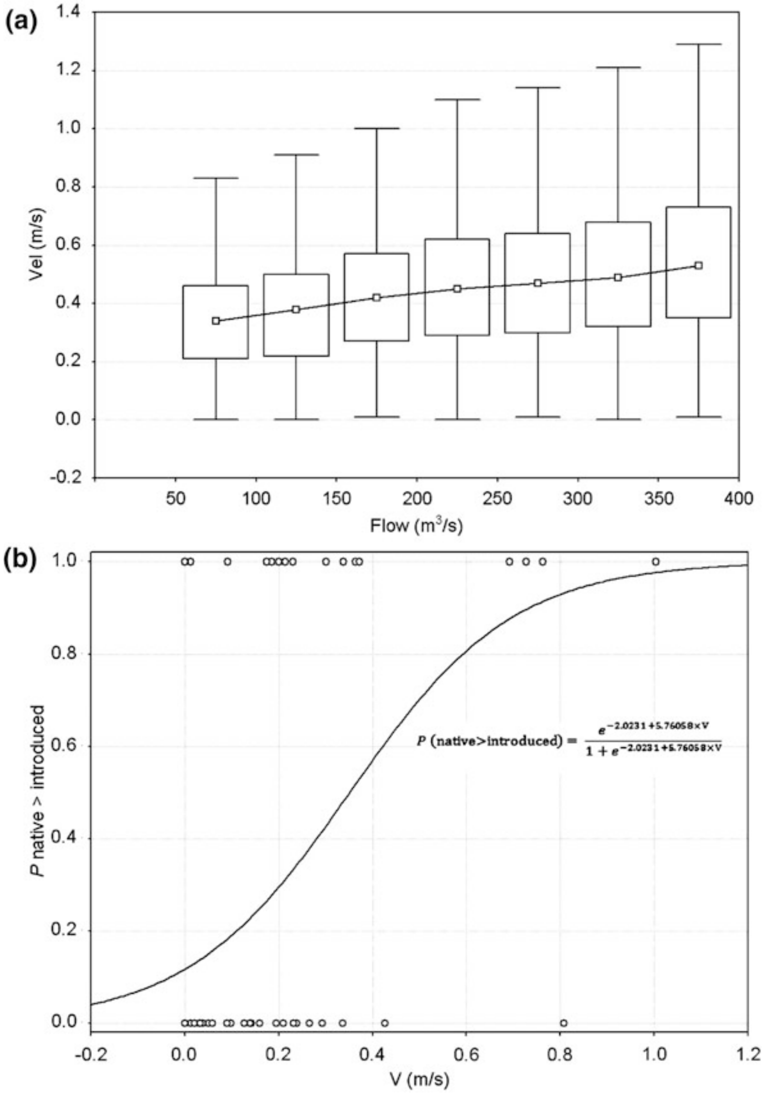

Fig. 9.3 Relationship between flow conditions and fish assemblage structure in the lower Ebro River: **a** trend line between flow and water velocity, the data points represent the median value, the boxes the percentiles 25 and 75 and the whiskers the minimum and maximum values; **b** probability of the establishment of a fish assemblage dominated by native species predicted by logistic regression (0 = >50 % introduced species; 1 = >50 % native species)

been monitored until recently and the data concerning extreme events is scarce; consequently a few cases are reported in the literature. One of them looked at the effects of the 1989–1990 drought on the sediments of the Bilbao estuary. An extreme variation in the trace metal contamination of sediments and bivalves from the Bilbao estuary was found, and growing sediment concentrations resulted from the reduced river flow raising the proportion of metal-binding organic matter within the system. In addition, the contrasting contamination pattern (Cd, Cu, Pb and Zn increased much more than Cr and Ni) suggested that water restriction measures promoted sewer corrosion and the subsequent production of metallic leachates. Metal levels in the local bivalve *Scrobicularia plana* reflected the temporal evolution observed in the abiotic benthic compartment, but its recovery to the typical values for the area was slower than that shown by sediments. These results constituted some prime field evidence of drought effects that should be born in mind when pollution and risk from climate change are assessed in estuaries.

The environmental impacts of the drought of 1989–1990 in Spain were also reported in the Ebro estuary, a highly stratified estuary in which the salt wedge penetrates the lower Ebro River when the runoff is lower than 400 $m^3 s^{-1}$ (Ibáñez et al. 1997). During the drought period, the river flow was very low all the time (about 100 $m^3 s^{-1}$), which caused the permanence of the salt wedge 32 km upriver uninterruptedly during 22 months (Ibáñez et al. 1995). This situation increased the level of eutrophication and lead to an exacerbation of hypoxia in the estuary (causing the disappearance of benthic fauna); salt intrusion in the alluvial aquifer was also reported. In the estuary of a small river in southern Spain (Palomares River) some environmental impacts were also reported due to a combination of the drought at the end of the 1990s and the construction of a dam (Clavero et al. 1999). The results of this study showed important biological and chemical changes in the sediment, especially a 100-fold increase in the rate of accumulation of phosphorus (up to 157 g P m^2 $year^{-1}$).

9.2.4 Responses and Adaptations of Wetlands and Lagoons

Mediterranean wetlands have been greatly reduced in area and changed by human activities. These changes have taken place since the Greco-Roman times. However, the greatest changes have occurred in the twentieth century, with a reduction of more that 60 % of wetland surface in Spain (Ibáñez et al. 2000). Reduced runoff and river flows due to drought and water scarcity may cause the loss of some wetland types that will no longer hold water long enough to support hydric communities. Species distributions will shift, and species extinctions may result particularly across fragmented or vulnerable landscapes. Accumulation of salts in wetlands will shift species-rich freshwater communities to species-poor salt-tolerant communities. Wetlands will differ in ecological response to these changes as the salinity and drying history of each wetland will determine its resilience. In the short term, some freshwater communities may recover but they are unlikely to survive and reproduce under long-term increased salinity and altered hydrology. In the long term, such salt-stressed wetlands with altered hydrology will need to be colonized by salt-tolerant species adapted for the new hydrological conditions if they are to persist as functional wetlands (Nielsen and Brock 2009).

However, the response of wetlands to extreme hydrological events such as flood and drought can be complex. Experimental studies of vegetation responses to climate have largely focused on responses to a trend in climate or to a single extreme event. However, studies have largely overlooked the potential for complex responses to specific sequences of extreme events. A recent study (Miao et al. 2009) found, on the basis of an experiment with seedlings of three types of subtropical wetland tree species, that mortality can be amplified and growth can even be stimulated, depending on event sequence. These findings indicate that the impacts of multiple extreme events cannot be modeled by simply summing the projected effects of individual extreme events but, rather, that models should take into account event sequences.

In the Iberian Peninsula, the effects of drought and overexploitation of water resources on wetlands have been severe in some areas but, in most cases, the existing information on responses and adaptations of aquatic ecosystems is scarce. In the Doñana National Park, some studies have reported negative effects of aquifer exploitation and drought on the integrity and functioning of wetlands (Suso and Llamas 1993; Serrano et al. 1999; Sousa et al. 2009). Another study reported some changes in the macrobenthic fauna of a Mediterranean Salt Marsh located in Catalonia during a drought in 1998 (Gascón et al. 2007). This study found a significantly higher diversity of species after the severe drought, caused by a decrease of the dominant taxa and the appearance of taxa, which were not found before.

The most dramatic case of wetland deterioration due to water scarcity and drought in Spain is clearly the case of Las Tablas de Daimiel National Park, located in the upper Guadiana Basin (Central "Meseta" of Spain), which has a semiarid climate. About half of the catchment surface is formed by important calcareous aquifers, and the hydraulic connection between surface and groundwater is high. A good number of wetlands of different types that form the main part of the UNESCO Biosphere Reserve called "La Mancha Húmeda" are located in this catchment. The irrigated surface grew from some 200–300 km^2 in the early 1970s to 1,300–1,400 km^2 in the early 1990s, mostly due to the pumping of groundwater from the main aquifer of the catchment. This new irrigated agriculture has been a driving force for the region's economic development, but it has induced dramatic changes in the catchment hydrology and has caused serious impacts on some wetlands (Fornés et al. 2000).

Las Tablas de Daimiel National Park is a series of wetlands that naturally originated from groundwater discharges from the Mancha Occidental aquifer. Despite the relatively large size of this aquifer, 30 years of intensive groundwater pumping have significantly depleted the water table. As a result, wetlands only remain functional due to artificial inflows (Castaño-Castaño et al. 2008). Drainage reduced the wetland area to one-seventh of its original value in eight years between 1965 and 1973, and watermills were destroyed in the 1960s. Water availability was reduced greatly between the late 1970s and the 1990s because of irrigation programs in the catchment area, which exhausted the groundwater aquifer. Their effects on plants were mediated by decreasing yearly average flooding and its variability. The combined effect of increased eutrophication and decreased water inputs reduced the *Cladium mariscus* cover 10-fold, reduced the extent of Charophyte meadows and three quarters of hydrophyte species were lost. The reed cover (*Phragmites communis*) increased 22-fold (Alvarez-Cobelas et al. 2001).

The protected area has been drying up for decades because of (mostly illegal) wells dug by farmers on the edges of the park to drain water away to lagoons and wetlands. The aquifer, which once fed the wetland, now lies 20 m below them. Farmers near the Park have perforated thousands of wells, some 100 m deep, and have spent years pumping out more water than goes into the aquifer. Furthermore, the Guadiana River, which used to flow into the Tablas de Daimiel National Park, has disappeared. The present situation is critical, due to the combination of unsustainable exploitation of the aquifer and the drought, which has lead to the almost complete drainage of the wetland in 2009. Intense summer heat in 2009 caused dangerous fires underground and now only 1 % of the surface of the Park (1928 Ha) remains wet. The dried organic matter below ground level has spontaneously combusted with help of oxygen filtering through cracks on the surface. The European Union launched an investigation into the crisis and gave to the Spanish government 10 weeks to explain how it plans to respond to the ecological disaster. Spain's environment ministry pledged to pump water over from the Tagus River basin, but the last time that was attempted, 95 % of the water was lost along the way due to infiltration and evaporation. Finally, in January 2010 waters diverted 150 km from the Tagus River began pouring from an underground pipe onto the National Park, but this is a temporary solution to try to stop the peat burning and recover some flooding of the wetland. In February 2010, a period of heavy rains partially recovered the status of the wetland. However, the present situation is critical and can become irreversible if efficient measures to reduce underground pumping are not taken.

Regarding the impacts of drought and water scarcity on lakes, the most relevant case in Spain is lake Gallocanta, in northeastern Spain, a highly fluctuating inland saline lake located in a closed basin at 1,000 m above sea level. The lake has an endorheic watershed of about 500 km^2, and its features make Gallocanta an outstanding climatic sensor, reflecting any slight change in the rainfall/evaporation ratio by a parallel change in water level (Rodó et al. 1997; Kuhn et al. 2010). Lake Gallocanta became dry in 1994 as it had also done in 1983, as a result of a severe decrease in rainfall. These two periods coincide with strong/very-strong warm phases of the El Niño-Southern Oscillation (ENSO) of 1982–1983 and of 1992–1993, which had effects all over the world. The lake is known to have dried out completely around 1965–1966, and at least two other drying-out phases in the present century are recorded in the sediment as differential mineralogical depositions. Strong negative anomalies in rainfall are also reported to have occurred, coinciding with these strong phases (Rodó et al. 1997, see Fig. 9.4). However, in the case of Gallocanta Lake, the effects of cyclic drought are not critical for the ecosystem, since the exploitation of water resources is not as intense as in Tablas de Daimiel National Park, and the lake tends to recover its functioning after the drought periods.

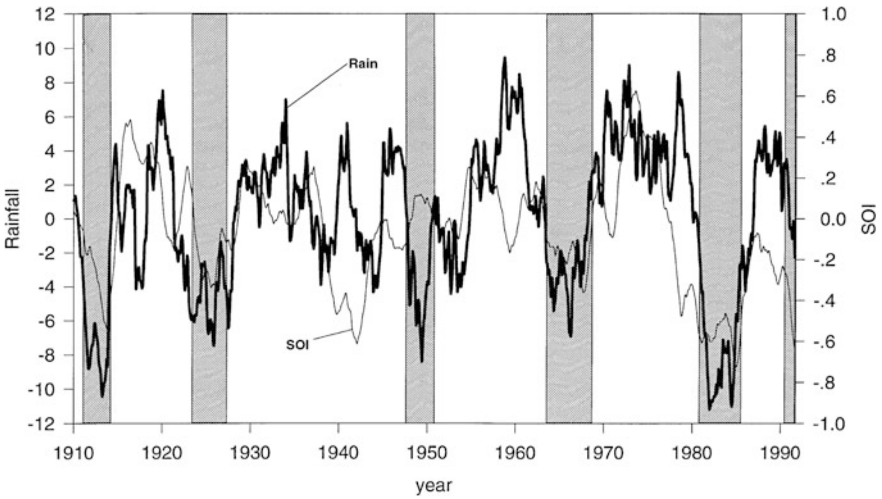

Fig. 9.4 Series of departures from long-term monthly mean rainfall in Daroca, near the Gallocanta lake (*thick line*) and Southern Oscillation Index (SOI, *thin line*). The series are centered five-year moving averages, with exponential smoothing applied to the end of the series to capture current rainfall minimum. *Dashed areas* indicate periods of severe rainfall deficit (*Source* Rodó et al. 1997)

9.3 Conclusions and Recommendations

The Mediterranean aquatic ecosystems of the Iberian Peninsula are adapted to cyclical drought under natural conditions, but at present they are severely impacted by water scarcity due to overexploitation of water resources. This situation will be aggravated by the increasing effects of climate change, since the Mediterranean is going to be one of the most impacted regions worldwide. Consequently, water policy must quickly shift towards a demand-management and ecosystemic oriented approach in order to reduce the total water use, increase the water efficiency, and restore the aquatic ecosystems.

One of the main measures to be urgently implemented for mitigating the effects of water scarcity in Mediterranean aquatic ecosystems is the establishment and implementation of a pulsing environmental flow regime, incorporating both minimum and maximum flows designed to maintain the crucial ecological functions and biodiversity. The natural range of variation is critical to maintain the integrity and dynamic potential of aquatic ecosystems; therefore, management should allow for dynamic change (Baron et al. 2002). Another important measure is the restoration of the aquatic habitats, especially the partial recovery of the hydrological and ecological connectivity that has been severely reduced by the construction of dams and other infrastructures. In this sense, the recovery of the sediment flow and the transit of fish through the reservoirs by means of appropriate by-pass systems should be a priority.

Future research should focus on quantifying the ecological effects of water scarcity at different spatial and temporal scales, developing specific ecological indicators of water stress, and also on determining and modeling the influence of environmental flows in maintaining biodiversity and ecosystem functions and services.

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Chapter 10
Ecological Responses and Interactions with Drought in the Southwestern United States

G. Darrel Jenerette

Abstract The effects of droughts on ecological systems can be dramatic with wholesale change to biotic community composition and marked alterations in ecosystem functioning that may be sustained after drought conditions are alleviated. Several recent advances in understanding ecological responses to drought are leading to improved theories of ecosystem functioning and the coupling between ecosystems and societies. An ecohydrological framework provides a comprehensive approach to understanding these effects through the coupling between ecological and hydrological processes. A key feature of many ecohydrological systems is their characteristic pulsed behaviors in response to moisture variability. An ecosystem services framework has recently been developed that can help quantify the potential impacts of droughts on society. By evaluating ecosystem services in the context of their required water uses, the effects of droughts can be better quantified and potentially mitigated. These paired frameworks of ecohydrology and ecosystem services are used to better understand historic, current and, likely, future consequences of droughts in the southwestern United States.

10.1 Introduction

Droughts have a strong ecological component in which reductions in moisture can substantially alter ecosystems. These drought-induced changes in ecosystem functioning can lead to important consequences for societal well-being. This chapter focuses on the ecological aspects of drought with examples specifically from the Southwestern United States. A nascent theoretical framework, ecohydrology, is being used to understand how the functional coupling between biota

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and hydrology are integral to whole ecosystem functioning and sensitivity to drought. Within this framework, the roles of pulsed dynamics are a potentially general ecosystem response to precipitation variability. The potential consequences of ecological responses to drought may often extend to large societal impacts, primarily through reductions in ecosystem services. This coupled framework of ecohydrology and ecosystem services can be used to better describe how ecological systems have responded to past droughts, likely current ecological conditions in reference to drought conditions, and potential future trajectories.

10.1.1 Drought and Ecological Processes

Drought is associated with many ecosystem and landscape changes. Within an ecosystem, drought can alter metabolism, nutrient cycles, disturbances such as wildfire, and community assembly processes, such as invasion by exotic species. At landscape scales, drought is associated with altered spatial heterogeneity, connectivity between ecosystems, land-cover change dynamics and, likely, scaling regimes. Ecological responses to drought occur at a variety of temporal and organizational scales. Ecological responses to droughts can also occur from seasonal, annual and decadal time scales, and meter to regional spatial scales. These responses derive from non-linear interactions between biological, societal, hydrological, and meteorological interactions. Perhaps paradoxically, periods of unusually large precipitation rates may lead ecosystems to expand such that they become dependent on larger precipitation inputs, and a return to normal precipitation inputs is associated with drought conditions. Consistent with hierarchical approaches, larger and longer droughts are associated with higher-scale ecological processes (O’Neill et al. 1986; Wu et al. 2005). A more extensive drought in both space and time will lead to a larger ecological response.

10.1.2 Multiple Patterns of Precipitation in the Western United States

In the southwestern United States, water availability is a key limiting resource for ecosystem functioning. Potential evaporation is much larger than precipitation throughout this region during most months of the year. Across the southwestern United States, heading inland from the Pacific, the timing of precipitation inputs vary dramatically with winter precipitation dominating the coastal regions and summer precipitation dominating farther inland regions. Southern California is generally classified as a Mediterranean ecosystem with the majority of precipitation inputs associated with large winter frontal storms originating from the Pacific. Moving more inland, Arizona has a bimodal precipitation regime. This region is strongly limited by water, and precipitation is generated by widespread and long-duration frontal systems in winter (Hastings and Turner 1965) and more localized and high-intensity convective storms in summer associated with the North American Monsoon (Carleton 1987). The two seasons of precipitation in the Arizona region lead to complex ecohydrological relationships in space and time (Drezner 2003; Jenerette et al. 2010). Along with the obvious temperature and light availability differences between seasons, several additional differences in rainfall are associated with seasonality. In comparison to winter rains, summer rains generally exhibit larger spatial variability, larger frequency of events, larger event intensity, more surface run-off, and higher evaporative demand (Goodrich et al. 2008). These summer–winter contrasts are common features of summer and winter rains globally and across the southwestern United States transect. Further inland, towards New Mexico, precipitation is again mostly associated with a single season in which the majority of precipitation arrives as part of the North American Monsoon. While not having large changes in the amount of precipitation across this transect, the timing and distribution of precipitation varies dramatically. These seasonal differences have large effects on ecosystem functioning across this seasonality transect, and set contrasting templates for understanding ecological drought.

10.1.3 Ecolohydrology as a General Approach for Understand Ecological Responses to Drought

Ecohydrology is a rapidly growing integration of ecosystem and hydrologic sciences, which emphasizes the coupling between hydrologic cycles and ecological functioning. It helps scientists understand how life depends on and affects the partitioning and chemical constituency of water on the continental surfaces (Bond 2003; Rodriguez-Iturbe 2000; Scanlon et al. 2005). The ecohydrologic perspective can be a useful bridge between engineering approaches for managing water flows and ecological approaches to understanding the biological, physical, and societal system encompassing the dynamics of water flows and, in particular, drought. The ecohydrologic perspective allows an explicit recognition of how water fluxes respond to processes and decision making at scales ranging from individuals to international treaties. In arid and semi-arid regions, the availability of water provides a fundamental constraint to biological activity (Jarvis et al. 2007; Jenerette et al. 2008).

Often, moisture arrives in discrete events leading to metabolic pulses of heterotrophic and autotrophic processes. These pulses of activity may affect ecosystems through cascades of responses, ranging from physiological, phenological, community structuring, and potentially evolutionary (Schwinning and Sala 2004). Understanding the role of intermittent wetting for ecosystem functioning has occupied ecologists for decades (Birch 1964; Noy-Meir 1973). Still, a mechanistic understanding of the dynamics of pulse events is not available to generate predictions of how whole ecosystems may respond to discontinuous and variable precipitation regimes (Jenerette and Lal 2005; Jentsch et al. 2007). At present, conceptual theories (Noy-Meir 1973; Ogle and Reynolds 2004; Reynolds et al. 2004) and some empirical evidence (Baldocchi et al. 2006; Chen et al. 2009; Huxman et al. 2004a; Jenerette et al. 2008; Lee et al. 2004; Williams et al. 2009) have been developed that describe how components of net whole ecosystem gas exchanges may respond to discrete precipitation through pulses of biological activity. Advances on this conceptual model, focusing on physiological responses, have suggested differential time delays in respiration and production pulses. These are based on contrasting rates of up- and-down regulation of physiological processes (Collins et al. 2008; Huxman et al. 2004b; Williams et al. 2009). Respiration (R), primarily shallow-surface soil heterotrophic processes, is expected to respond nearly instantaneously to a precipitation event with a rapid increase that gradually relaxes to a base state. Gross ecosystem production (GEP), in contrast, requires time for moisture to be transported through the plant and up-regulation of plant processes, followed by maintenance of maximum photosynthetic capacities. It then requires time for a down-regulation of activity as the ecosystem dries. Net ecosystem CO_2 exchange (NEE) is expected to have a complex trajectory reflecting the distinct responses of respiration and production pulses. This complexity has resulted in an unknown net ecosystem carbon balance due to discrete precipitation events.

Evidence helping to refine and support a theory of physiological pulses is developing through experiments conducted in the laboratory and field, and observations of natural variability from whole ecosystems. Because of the rapid responses of soil respiration to wetting and the potential to conduct small-scale experiments, more information is available for the soil heterotrophic component of whole ecosystem pulse events than any other component. Extensive studies of soil efflux associated with drying-rewetting cycles from experimental (Fierer and Schimel 2003; Sponseller 2007) and observational (Baldocchi et al. 2006; Jenerette et al. 2008; Lee et al. 2004; Xu et al. 2004) research have documented nearly instantaneous up-regulation, followed by down-regulation lasting for several days. The photosynthetic response is less obvious with only a few field experiments following individual events (Ignace et al. 2007). In one of the first analyses of whole ecosystem-estimated GEP pulses, up-regulation appeared to take between 10 and 20 days, following an initiating precipitation event (Williams et al. 2009). Even fewer studies have fully examined pulse-derived NEE fluxes, and portioned these into R and GEP in experiments (Chen et al. 2009; Huxman et al. 2004a) and observations of natural variability (Williams et al. 2009). None of these have estimated the overall net C effects of pulses. A clear implication from these studies has been the need for an expansion of ecosystem pulse theories to provide a more mechanistic explanation that can generate quantitative predictions and be evaluated empirically (Collins et al. 2008). Such advances in quantitative theory will improve capabilities to observe and experimentally evaluate pulse dynamics and estimate whole ecosystem net carbon consequences of discrete precipitation events. However, this research is still insufficient. Precipitation also induces phenological pulses after sufficient precipitation has arrived to cross thresholds in soil moisture. At these thresholds, many plants will initiate their growing season and cause large changes in leaf area, biological capacity for photosynthesis, and respiration (Jenerette et al. 2010). These phenological pulses lead to large reorganization of dryland ecosystems with strongly contrasting sensitivities to environmental conditions, compared to pre-growing season conditions. Even less is known about how precipitation-induced pulses affect community assembly or evolutionary dynamics of species (Schwinning and Sala 2004).

In the context of pulsed ecosystem dynamics, meteorological droughts can be translated into ecological droughts through altered amounts, timing, and distribution of precipitation. For the same amount of precipitation, a distribution among five large events will induce a different ecological response than a distribution among 20 small events. The many small events may each be sufficient to generate physiological pulses in the soil, but may be insufficient for plant pulses of activity. However, if the timing of the 20 small events occur in close proximity, for example, over the course of a single month, these water inputs may instead be sufficient to generate an initiation of plant growing season.

10.1.4 Coupling Ecological Drought to Societal Impacts

Beyond direct impacts to ecosystems, ecological droughts are also associated with a reduction in the availability of ecosystem services—processes and characteristics of ecosystems that directly or indirectly provide benefit to societal well-being (Daily 1995; Daily et al. 1997). An ecosystem services framework is quickly becoming useful for describing the collection of ecological processes that directly relate to societal needs (Carpenter et al. 2009; Luck et al. 2009; Nelson et al. 2009). Ecosystems services include a broad range of societal benefits derived from functioning ecosystems, including aesthetics, biodiversity, climate regulation, disease control, drinking, energy, erosion regulation, fiber production, fire protection, flood control, food production, pest regulation, pollution removal, recreation, sanitation, water capture, water purification, water storage, and wood production. The production of nearly all ecosystem services will be reduced in response to drought through reduced biological functioning. At the physiological level, reduced water availability can lead to stomatal closure and a reduced capacity to uptake CO_2 (Farquhar and Sharkey 1982). This can lead to reduced plant production of material goods, carbon sequestration, and other services. Transpiration also provides direct services through a localized cooling associated with energy required for vaporization (latent heat), which can lead to local temperature reductions (Akbari et al. 2001). In many heat-prone regions, transpiration fluxes may have a societal benefit by potentially reducing health risks and peak energy demands associated with extreme heat events. Reduced water availability will similarly reduce the capacity for plant-derived evaporative cooling. Recent patterns in Phoenix, Arizona, have suggested water uses and its sensitivity to climate forcing can vary substantially within a city (Balling et al. 2008; Jenerette et al. 2007). Many additional uses of water may not be directly associated with any ecosystem service, such as endangered-species habitat; however, these uses are also critical and should be included in allocation decisions (Baron et al. 2002; Jackson et al. 2001).

Among all of the water uses by society, outdoor irrigation is dominant. Agricultural production accounts for a large portion of regional water use. Beyond traditional food crops, irrigation is used substantially for landscaping within the city. The amount of irrigation water needed to promote growth of planted vegetation is partly related to the carbon uptake water-use efficiency of the crop or landscaping species—the amount of water that is lost in transpiration from the leaf stomata per amount of carbon gained. Irrigation efficiency is also associated with the amount of evaporated water lost during plant growth. The degree of evaporative loss is a function of various factors, including environmental conditions (for example, vapor pressure deficit and temperature), soil type, mulch or cover type, and irrigation methods. Thus, for a given crop or landscape species, the irrigation efficiency is assessed by the amount of water transpired, versus the amount of water evaporated. More broadly, water-use efficiency for the production of different ecosystem services could be similarly estimated (Jenerette and Alstad 2010). Potentially, water use efficiency-based approaches could help in allocating between different uses by deciding how best to use water for a given ecosystem service to maximize the production of societal needs with minimal water requirements. Such approaches may be especially useful for maintaining required ecosystem services during drought periods.

An example of human appropriation in the most populated region of the southwestern United States is the Los Angeles water system. Los Angeles uses extensive amounts of water, with large fluxes associated with irrigation of agricultural lands and recreational landscaping activities. The 2000 U.S. Geological Survey compilation of freshwater usage for the five-county LA region documented 497 ML/day for domestic, 280 ML/day for industrial, 6,651 ML/day for irrigation, 125 ML/day for aquaculture, 223 ML/day for livestock, 18 ML/day for mining, and 12 ML/day for thermoelectric (Hutson et al. 2004). Within these highly urbanized counties, irrigation consumes 85 % of the total water used. Los Angeles' hot and dry environment results in large evaporative demand, and any vegetated surface can use extensive amounts of water. Average estimated potential evapotranspiration derived from California Irrigation Management Information System (CIMIS) network for Los Angeles exceeds 1,200 mm/year. Within the city of Los Angeles, the Department of Water and Power estimated in 2003–2004 that 68 % of water used was for domestic household, 19 % of water was used by industrial and commercial operations, and irrigation accounted for less than 1 % of water used (Department of Water and Power 2005). Likely, much of the domestic household use was associated with individual homeowner landscaping, again highlighting unknowns in water fluxes for systems that are well-monitored and documented.

10.2 Responses and Adaptations of Ecosystems to Drought: Past, Present, and Future

10.2.1 Historic Precipitation Variability

The southwestern United States has a history of widely varying climates and extensive drought. Much of the current desert regions were more temperate, supporting extensive forests and grasslands, as recently as 5,000 years ago (Ortega-Rosas et al. 2008). Historically, droughts in this region lasting for centuries have been suggested from historic lake records (Stahle et al. 2007). At glacial-interglacial periods, the wide variation in climate conditions again varied over millennial time scales. These patterns lead to cyclical build-up of biological material during moist periods and ecosystem decay during drier or drought periods.

Droughts are a regular occurrence in the recent history of the southwestern United States region, as water inputs are associated with two dominant ocean-atmospheric cycles: the patterns of El Nino/La Nina and the Pacific Decadal Oscillation (PDO). El Nino/La Nina cycles are characterized by changes in surface water temperatures in the tropical eastern Pacific Ocean. El Nino events, periods of unusually warm surface temperature, tend to bring more winter precipitation and warmer summer temperatures to the Southwestern United States (McPhaden et al. 2006). La Nina events tend to have opposite effects. Less understood than El Nino/La Nina, the PDO is characterized by surface temperatures of the northern Pacific Ocean, with contrasting warm and cool phases (Mantua and Hare 2002). PDO signals have been reconstructed as far back as a millennia, using tree-ring analyses (D'Arrigo et al. 2001; MacDonald and Case 2005). The effect of these decadal-scale changes in moisture conditions can strongly impact ecosystems in the southwestern United States (Alftine et al. 2003). Recent evidence of present-day substantial carbon losses following a decade of elevated conditions are consistent with these connections (Scott et al. 2009b).

Two substantial droughts have occurred in the recent history that have generated widespread changes in ecosystems and landscapes, with concomitant impacts to the production of many ecosystem services (Hoerling and Eischeid 2007). The 1950s drought resulted in continent-wide reductions to agricultural productivity, and the interior United States was popularly referred to as a dustbowl. The 2000s drought, which in some parts of the region have lasted the entire decade, has been overlayed with an exponential expansion of urbanization (Jenerette and Wu 2001; Radeloff et al. 2005), which has put additional demands on water deliveries and expected ecosystem services (Luck et al. 2001). In many respects, higher temperatures during droughts, altered species compositions, increased nutrient deposition, and more fragmented landscapes will lead to novel ecological responses to reduced water availability.

Along with these annual-scale droughts, perturbations to seasonal precipitation distributions can lead to seasonal droughts that may have longer-term consequences. During the past decade, the contributions of winter precipitation has been reduced throughout this region with fewer changes associated with summer rainfall (Scott et al. 2009b). It is also associated with changes in jet streams and projected to continue in the future (McAfee and Russell 2008). This reduction in winter precipitation may lead to systematic changes in future ecosystem dynamics across the southwestern United States, with greater changes associated in the more western parts of the transect that depend primarily on winter precipitation.

10.2.2 Present-Day Unusual Responses to Drought

At present, in early winter 2010, Southern California is in a drought that has lasted since 2006 (California Department of Water Resources). For the 2009–2010 winter season, early January snowpack was nearly 30 % below expectations, based on normal climate patterns. Water storage in many reservoirs is less than 50 % capacity. Restrictions that are being implemented on outdoor use will then be associated with expected reductions in ecosystem services—notably agricultural production in the region. At present, it appears the two major oceanic circulations affecting this region suggest a cool PDO condition that may be near the end of its phase, and El Nino conditions are likely for the remainder of 2010. These conditions could suggest short-term and longer-term increases in precipitation; however, interactions of these processes with long-term cycles, such as PDO or climate change, are poorly understood.

Of particular concern is that the effects of droughts in the present may be qualitatively different than many droughts in the past. In the present era of a warming climate, hydrologic droughts may become more severe and extensive as soil temperatures increase evaporation and larger proportions of rain events occur in discrete larger events (Douville et al. 2002). In combination with increasing temperatures and changes to atmospheric chemistry, several unexpected ecological responses are occurring. The most recent drought, circa 2000, was associated with a relatively new ecological response of widespread tree mortality, which had not been observed in prior droughts (Breshears et al. 2005). While not a clear indication of drought due to climate change, this event is an example of the consequences of such climate change-induced droughts (Adams et al. 2009).

Occurrences of widespread tree mortality have become more common throughout the earth (Allen et al. 2010). This observation has led to a debate both on the causes and implications of widespread mortality phenomenon for understanding ecosystem functioning in response to likely future droughts. The mechanisms of this phenomenon are poorly understood—ecologists have been examining the initiating and dispersal process much more than mortality. Currently, two dominant hypotheses suggest pathways for mortality drought responses (McDowell et al. 2008). First, the severity of the drought may be associated with xylem disruption through cavitation. In contrast, the duration of a drought may be associated with carbon starvation as a chronic response to respiration exceeding photosynthesis. The implications of these findings are that both processes may increase in frequency with expected temperature increases. Recent experimental evidence has supported this prediction in a large glasshouse facility (Adams et al. 2009).

When not associated with plant death, moisture variability in the southwestern United States is leading to unexpected shifts in plant community composition. For example, in the Sonoran Desert nighttime minimum temperatures have increased substantially (Weiss and Overpeck 2005). These changes have altered the timing of soil moisture increases or the alleviation of seasonal droughts by delaying it into the winter. These conditions have then led to selection of more cold-tolerant species in desert annual communities, in contrast to the general warming observed in this region (Kimball et al. 2010).

A recent example from a severe drought in 2004–2005 throughout southeastern Arizona highlights these changes (Scott et al. 2010). Within this region, a monitoring network of whole ecosystem carbon dioxide flux systems have recently been installed in several representative ecosystems (Scott et al. 2009a). In a historically native grassland ecosystem, the drought period was associated with a large net efflux of carbon dioxide from the ecosystem and widespread mortality of the native grasses. In the year following this die-off event, the ecosystem became dominated by native annual forbs. However, the forb species were much less resilient to invasions and, again, in the following year the ecosystem was invaded by exotic bunchgrasses. These exotic grasses had overall higher annual water use efficiency, predominantly caused by an earlier phenological timing of green-up. These rapid shifts in community structure and concomitant effects on ecosystem functioning may be a common sequence in response to drought. The punctuated drought event, coupled with a nearby invasive species, led in this case to sustained changes in biological functioning.

In highly managed systems of the southwestern United States, droughts are also altering ecological functioning indirectly (Jenerette and Alstad 2010). Droughts induce watering restrictions that reduce the production of ecosystem services. For the first time in its history, Los Angeles, instituted mandatory water restrictions on outdoor irrigation. These policies can lead to large reductions in ecosystem services. Recent increased interest in protecting rare and endangered species has led to large allocations of water in California reserved for endangered fish reproduction. This case highlights how societal processes can cascade down to either impose or alleviate ecological droughts independent of meteorological and hydrological conditions.

10.2.3 Future Projections of Ecosystems to Directional Climate Changes

What do future climate conditions portend for ecological responses to drought? Likely scenarios of climate change predict a general drying of the southwestern United States, which will be associated with climate normals at historic drought levels (Hoerling and Eischeid 2007; Seager et al. 2007). Throughout the region, several lines of evidence suggest winter rains will be more affected than summer (McAfee and Russell 2008). In association with these changes to expected normal climate conditions, more severe droughts will likely occur with greater frequency. These low-precipitation and high-temperature droughts will likely cause widespread changes in communities and material storages.

Ecosystem responses may include an overall reduction in activity and a concentration of activity within pulsed responses to precipitation events. Likely, the consequences of recent droughts will be harbingers of future ecological drought consequences. These changes could lead to reduced carbon sequestration capacity, material production, cooling capacity, and aesthetic services. Reducing these services will have direct and indirect consequences on societies with likely impacts including increased energetic costs, expected climate changes at regional and global scales, and reduced recreational amenities.

Mitigation strategies for maintaining ecosystem services are currently being evaluated, and the maintenance of intact ecosystems with sufficient water resources is becoming more desired by societies. Extensive research is being conducted on developing more drought-resistant crop plants and farming practices that maintain biological functioning (Lal 2004). Planners in California are implementing new restrictions and are quickly moving to develop additional management practices to reduce outdoor water use. Concepts of ecosystem service water-use efficiency seem to have some potential to help decision-making for water allocations. For example, if two practices provide the same ecosystem services but one uses much more water, recommendations could be made in favor of the other more efficient water-use strategy.

10.3 Conclusions

By evaluating ecological droughts as a key link between hydrologic variability and societal needs for ecosystem services, a consistent framework for understanding biological responses and interactions with society and meteorology can be realized. Ecohydrology, with an emphasis on pulse responses to precipitation variability, provides an initial theoretical approach to understand ecological droughts. An ecohydrological approach suggests a water-use efficiency of the ecosystem services required for societal sustainability could be a useful analysis to evaluate water-diversion strategies. Droughts are likely expected to increase in frequency, severity, and duration throughout the southwestern United States. These will likely cause changes in community composition and decreases in ecological functioning that, combined, lead to negative societal impacts. Likely, these changes are happening throughout the world, and an integration across ecosystems globally will improve understanding and be a source for multiple management options.

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Chapter 11
Agriculture, Water Mismanagement and Ecosystem Transformations in the Cuatrociénegas Valley in the Chihuahuan Desert, Mexico

Irene Pisanty, Cristina Pérez y Sosa and Gabriel Gálvez

Abstract Due to water overexploitation mainly related to agricultural activities, water levels are diminishing in the Churince System, one of the wetlands of the Cuatrociénegas Valley, in the Chihuahuan Desert of northeastern Mexico. Soil subsidence is increasingly frequent, leading to the formation of numerous sinkholes or *hundidos* (locally known as *abras*), formed by the alterations of soil structure due to water loss from the main water bodies. Sinkholes in the study area can be small (only a few square centimeters), or large (six or more square meters), depending on their age and how each one is formed. Some doubts remain about the effects of the overexploitation of water in the Cuatrociénegas Valley and also in the surrounding valleys on the instability of the Churince System, but sinkholes are continuously opening, and water levels are quickly decreasing. We registered the formation of sinkholes—their size, depth, water level, and the colonizing pattern of the plants that occupy them. We also recorded the population dynamics and growth form of *Samolus ebracteatus* var. *coahuilensis*—one of the main colonizing species. We concluded that sinkholes are constantly appearing and that their physical and biological characteristics are very dynamic. Additionally, these sinkholes are indicators of environmental disturbance and their formation should be used as an early warning system of hydrological changes in this region in which ecosystem integrity is being affected. We suggest that *Samolus ebracteatus* var. *coahuilensis* is an indicator of humid microhabitats. Changes in its distribution and in its population dynamics indicate changes in superficial underground water caused by the alteration of the hydrologic system.

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11.1 Introduction

Water mismanagement has affected ecosystems all over the world, including arid zones in which natural scarcity of water can increase through unsustainable practices that can create critical ecological and social situations. Frequently, the lack of accurate technical and scientific knowledge makes it difficult to include important hydrological, geological, ecological, and social considerations while deciding how and where to implement specific management strategies. Far too frequently, the available information is ignored and precautionary measures are avoided in order to favor economic and/or political interests of specific groups. In this scenario, physical and biological indicators can help prevent an increase in environmental degradation.

Due to inefficient irrigation, both in commercial fields and in *ejidos* (a system of common land ownership), in the different valleys of the Cuatrociénegas region, Coahuila –in the northeastern part of Mexico—a unique system of wetlands in the Cuatrociénegas valley has been under siege. This valley, or *bolsón*, is located 80 km to the north from the city of Monclova, at 25°45′00’″ and 27°00′00″ N and 101°48′49″ and 102°17′53″ W, where the climate is arid with an average yearly precipitation of 219 mm. Summer is the rainy season. Temperature variation throughout a year is very wide, ranging from under 0 to 50 °C (Fig. 11.1). The Cuatrociénegas Valley is unique in many biological, hydrological, and geological ways (Espinosa et al. 2005). It was declared a natural protected area (*Área de protección de recursos naturales*) by the National Commission of Protected Areas in 1994. In 2007, the area of protection expanded and now covers 801,000 ha, which includes the surrounding mountains (CONANP 1999; INE 2009; DOF 1994).

The Cuatrociénegas valley is characterized by a system of wetlands. Five distinct water flow systems have been identified: Churince, Garabatal-Becerra-Río Mesquites, Tío Cándido-Hundido, Santa Tecla, and El Anteojo. Some 300 bodies of water constitute a very complex interconnected system (Souza et al. 2006; Aldama et al. 2007; Wolaver et al. 2008) that include geothermal springs, ponds, marshes, playa lakes, and streams (Evans 2005). These water bodies have variable depths (from less than 2 to 10 m), temperature (from 15 to 35 °C), and salinity (pH from 7.6 to 8; 314 to 810 mg/L Na). Salinity increases towards the end of the flow systems (Evans 2005).

Not enough is known about the hydrological structure and history of the zone. Some of the groundwater in the Cuatrociénegas Valley is captured through local recharge within the San Marcos and La Madera ridges, but some interbasin inflow must be contributing to the ground water discharge (Cortés et al. 2002; Johannesson et al. 2004). The Aurora and Cupido formations in this region have very permeable aquifers (Evans 2005). Springs can be found on both sides of the Sierra de San Marcos; hot and cold springs discharge close to each other. On the west side of the Sierra de San Marcos, where the Churince System is located, spring discharge is high and depends both on groundwater flow and recharge from

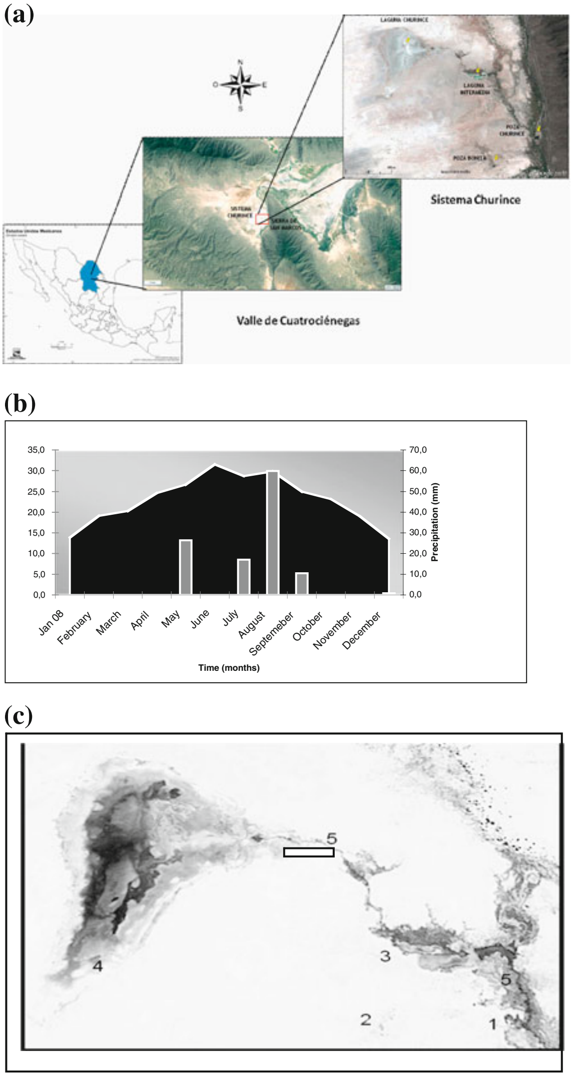

Fig. 11.1 Study area. **a** Geographic location. **b** Climogram (2008). **c** Churince system: (*1*) Poza Churince; (*2*) Poza Bonita; (*3*) Laguna Intermedia; (*4*)Laguna Churince (Laguna Grande); (*5*) Río Churince. The square shows the sampling area. Poza Churince and Poza Bonita are connected underground

precipitation (Wolaver et al. 2006). All of these water bodies are located in a very arid matrix, and generate distinct water and riparian microenvironments. They are more frequently found close to the piedmont of the San Marcos ridge, in the southeastern part of the valley.

The Cuatrociénegas Valley has a high biodiversity that includes 60 species of mammals, 60 reptiles, 145 birds, eight amphibians, 17 fishes, 27 crustaceans, and 883 vascular plants related to different microenvironments (including lotic, lentic and riparian habitats), different types of soils and one of the few gypsum dunes sites in the world (http://www.desertfishes.org/cuatroc/organisms.php; Villarreal-Quintanilla and Encina-Domínguez 2005). With its 70 endemic species, the Cuatrociénegas

Valley has more endemisms than any other place in North America (http://www.desertfishes.org/cuatroc/organisms.php). Conabio considers it a priority area (CONABIO http://www.CONABIO-gob-mx/conocimiento/regionalización/doctos/rtp_069.pdf). It is a Ramsar site, due to the importance of its migratory bird species, which find water and refuge while crossing the arid lands of North America. It is also in the migratory route of Monarch butterflies. Unique stromatolites composed of ancient bacteria and cyanophytes related to the first living organisms on Earth can be found in some of the valley's lakes and springs (INE 2009, Espinosa et al. 2005, Souza et al. 2004, 2006). These organisms thrive due to very low phosphorus contents, which are the lowest reported for continental waters (Minckley and Jackson 2008). Vegetation types were described by Pinkava (1984).

Conservation threats include a deficient recreational use of lakes, ponds and springs, overgrazing by horses and donkeys, gypsum extraction (now regulated) and, of major concern, an overexploitation of surface and ground water used in agriculture. Perforation of wells for commercial agricultural activities has been constant and not properly regulated. Additionally, expansive channels have been built to take water from its original source to agricultural fields within and beyond the basin. The first channel, known as Saca Salada, began operating in 1898. In 1996, a second channel, known as Santa Tecla, was opened (Evans 2005). Since these are open channels, evaporation is high. Additionally, water extraction to irrigate expanding alfalfa fields in the nearby valleys of Ocampo, Calaveras, and El Hundido is altering the valley's aquifer (Rodríguez et al. 2005).

The main cultivar in the region is alfalfa (*Medicago sativa*), which demands a great amount of water, but can withstand high-salinity levels. In the Cuatrociénegas region, alfalfa has been cultivated with surface water for more than 15 years, and large enterprises produce alfalfa for their milk cattle. Irrigation has caused a considerable decline of groundwater levels and has dried up surface water that, otherwise, would have continued flowing into the Cuatrociénegas Valley. The hydrology of Cuatrociénegas and of the surrounding valleys is not well known, and contradictions between different technical reports and studies done by different stakeholders persist (Lesser and Associates 2001; Johannesson et al. 2004; Aldama et al. 2005; Evans 2005; Souza et al. 2006; Wolaver et al. 2008). Further details of this flow are still needed, and the karstic nature of the mountains and the valley of this basin add to the difficulties in understanding this complex system (Bailly-Comte et al. 2009). However, the loss of water is unquestionable (Johannesson et al. 2004; Rodríguez et al. 2005; Wolaver et al. 2006).

In 2000, three new alfalfa fields were established in the neighboring El Hundido Valley. Without the necessary legal permits, approximately 5,000 ha of xerophylous vegetation, which included endemic species as well as species under protection, were cleared, numerous wells were opened and large alfalfa fields were established. A particularly polemic assessment about the potential communication between the Cuatrociénegas aquifer and that of El Hundido was the core of a confrontation that led to the temporary suspension of water extraction of wells in the El Hundido Valley. The main controversy is whether aquifers from the two valleys communicate or not. This is a relevant issue in order to establish the impact that water extraction in El Hundido could have in Cuatrociénegas. Alfalfa fields expanded in El Hundido and, at the same time, Laguna Churince, one of the two large terminal lakes of the valley, started desiccating quickly. Since these lakes have seasonal fluctuating levels, some of the local stakeholders did not consider the sudden decrease of the lake's volume relevant, even if the lake had never been so small. In 2004, sinkholes started appearing along the last part of the stream, close to the lake, at higher rates than what local people, conservationists, and scientists working in the region recognized as normal (S. Contreras, V. Souza, A. Espinosa, JC Ibarra, pers. com.). Some scientists and conservationists, as well as governmental groups, considered this a serious and relevant change that would deteriorate the environment and could lead to the total loss of the system; other groups denied such an association.

Unfortunately, less than 3 years after the above-mentioned events, Laguna Churince dried out completely and mud cracks have appeared. This process coincided with the increase of water extraction at El Hundido, and some biologists (Souza et al. 2006), and hydrologists (Megan et al. 2006, Rodríguez et al. 2007; Wolaver et al. 2008) consider that they are certainly correlated. Biological evidence provided by Souza et al. (2006) for bacteria indicates a potential communication between water bodies in the Cuatrociénegas Valley and in the El Hundido, albeit not continuous, as frequently happens with karstic substrates. Still, further hydrological studies are needed to understand the details of these systems.

Sinkholes can be of different shapes, sizes, and depths, and water can be found continuously or discontinuously in some of them. They are formed because water that flows underground away from lakes, ponds and streams dilutes salts in the soil, which looses cohesion and subsides. This process is initiated due to the loss of stability of underground water (Agueda-Villar 1983; Palmer 1991). Sinkholes form a sort of archipelago of discrete riparian habitats that are colonized by a reduced number of species that can stand high salinity levels. Water is frequently accumulated in these microhabitats, where humidity is higher, temperatures are milder and more stable than in the flatland, and their inhabitants are protected from strong desert winds.

In this project, we monitored the formation and the physical and biological characteristics of sinkholes along the last part of the Churince system to determine the formation rate of these structures, their dynamics, and the plant colonization process that takes place in most of them. With this information, we built a model to project how the system will behave in the future if the present conditions prevail. Additionally, we studied the demographic dynamics of *Samolus ebracteatus* var. *coahuilensis*, one of the characteristic plant species that colonize riparian habitats and sinkholes in the valley.

The dynamics of sinkholes and of a dominant species of the study site can help us identify physical and biological processes that can act as early warnings of the destabilization of the water system of this region.

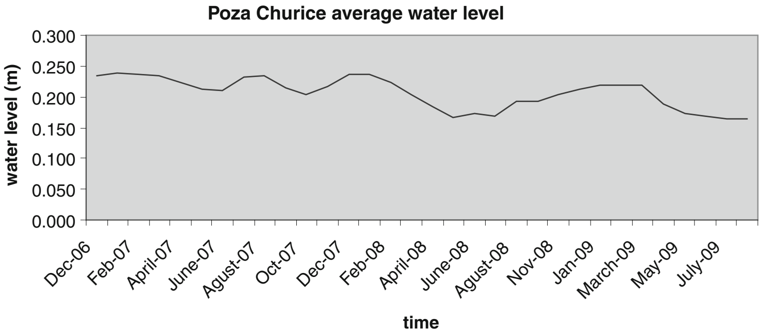

Fig. 11.2 Water level in Poza Churince (December 2006–July 2009). *Source* Instituto Nacional de Ecología available at http://www.ine.gob.mx/emc-cuatrocienegas-mediciones. Last reviewed: February 2010

11.2 Methods

11.2.1 Study Site

The Churince system (Fig. 11.1) is located in the northeastern part of the Cuatrociénegas Valley. It is composed by the Poza Bonita, Poza Churince, Río Churince, Laguna Intermedia and Laguna Churince (or Laguna Grande), which is the terminal lake of the system. The spring in Poza Churince provides water to the rest of the system. The water level of the whole system, a main landscape and ecological trait of the valley, is diminishing (http://www.ine.gob.mx/emc_cuatrocienegas_mediciones), as well as the flow from the spring (R. Zargoza and J.C. Ibarra, pers.com.); specifically, Laguna Churince had lost most of its water by 2006. By mid 2009, this pond and the last part of the stream were dry, and the streambed was covered by mud cracks. In this part, some water accumulated again as winter approached, because temperature and evaporation diminish during the cold season, allowing some recharge water coming from the Sierra de San Marcos to accumulate temporarily, before it evaporates again. Piezometric measurements have been taken only recently. Changes in water level in Poza Churince are shown in Fig. 11.2; however, no data are available for Laguna Churince.

11.2.2 Sinkholes

As a first stage of this study, sinkholes were registered from January 2008 to January 2009, along the last 300 m of the stream, where they concentrate in a surface area of 35 × 100 m. Pinkava (1984) described the region as lacking vegetation because it is covered with sparse and short plants. The Primulaceae *S. ebracteatus* var. *coahuilensis* was not reported in this region of the valley in

Table 11.1 Size categories for sinkholes

Category	Area (m^2)
1	0.003–0.05
2	0.051–0.1
3	0.11–0.2
4	0.21–0.4
5	0.41–0.6
6	0.61–1.6
7	More than 1.6
8	Closed

Pinkava's pioneer study, but it is now prevalent both in the flatland, where it dominates in the landscape, and in the sinkholes.

All sinkholes were censed and tagged. Length, width and depth, as well as the absence or presence of water was recorded. We monitored these parameters every 2 months during 1 year, and we also identified newly formed sinkholes that were characterized in the same way. We registered the establishment of plants in the new sinkholes in order to identify possible colonization patterns and indicator species of specific colonization stages.

Sinkholes were categorized according to their size (Table 11.1) by measuring their perpendicular axis and approximating the sinkhole's shape to an ellipse. Area was calculated with the formula $A = \pi\,(\mathbf{a_1/2})(a_2/2)$, where $\mathbf{a_1}$ and a_2 are the main perpendicular axis of an ellipse.

Since the size of some sinkholes changed and the proportion of each category was variable through time, we categorized them according to their area, and we built a Lefkovitch transition matrix (Caswell 2001; Vega and Montaña 2004; Gotelli 2008). We then built a transition diagram, based on the probability of each category to pass to a higher (growth) or a lower (retrogression) one, or to remain as it was (permanence) (Silvertown et al. 1993). The size of sinkholes can increase because the borders collapse making them larger (growth) or smaller (retrogression) due to the accumulation of soil close to the border. Based on the iteration of the transition matrix, we projected the behavior of this sinkhole "population" through time, which allowed us to determine how it will behave, provided environmental conditions stay constant.

11.2.3 Population Dynamics of Samolus ebracteatus (Primulaceae)

S. ebracteatus is a herbaceous species member of the Primulacea family. Plants are short, and have simple verticillate leaves (Fig. 11.3). Flowers are actinomorphous and have five petals that fuse in the base, five stamens are inserted in the floral tube; they are numerous, color goes from almost white to dark pink. Inflorescences form umbellas (Ocampo 2000).

Fig. 11.3 *Samolus ebracteatus* var *coahuilensis*, mature plant

To evaluate the population dynamics of *S. ebracteatus,* we divided the study area in thirds, and followed a 80 m transect in each of them. Length of the transects was determined by the area in which the species can be found. Along the transects, a 5 × 5 m square was placed every 15 m, and all individuals found in each square were numbered and tagged. New squares along the transects were considered until three consecutive ones lacked *S. ebracteatus*. If the transect crossed a sinkholes, individuals in them were considered. Transect one had six squares, and transects two and three had five each. A total of 660 plants were initially marked along the transects.

Though this species produces ramets, they are not easily identified; thus, sampling was based on physiological individuals that were, at least superficially, not connected among them. In each individual, we counted the number of green and dry rosette-like branches (called "rosettes" hereafter) and the number of flowers and fruits. Plants were categorized by the number of green rosettes, and seedlings were registered and categorized by the number of leaves they had (Table 11.2).

After identifying the plants in January 2008, we monitored them every 2 months (May, July, September, November 2008, and January and March 2009) to get their vital rates; new individuals along the transects were also registered. New individuals could be seedlings (categories one and two, except when in the

Table 11.2 Categorization of *Samolus ebraceatus* according to the number of leaves and of green rosettes

Category	Description
1	From 1 to 4 leaves
2	From 5 to 10 leaves
3	1 rosette
4	2 rosettes
5	From 3 to 5
6	From 6 to 10
7	From 11 to 15
8	More than 16

latter case it was certain they resulted from retrogressions) or ramets (clones), formed by a single well-defined rosette. Individuals growing both in sinkholes and in the flatland were considered throughout the transects. The dynamics of the population was represented by a life cycle diagram. Additionally, a census of all the newly formed sinkholes was made and the presence of *S. ebracteatus* was registered, whether or not they were part of the transects, in order to determine the colonization pattern of this species.

Identifying the parental plants of clones (category three) was impossible in the field, because underground structures are extremely thin and fragile near the surface, or too deep below it. Consequently, clone production by established individuals was assumed to be proportional to the number of new rosettes they could produce. Fecundity was estimated through several steps (Valverde and Silvertown 1997). First, 100 infrutescens were randomly collected in March 2008, and the average number of seeds per fruit was determined. Then, the number of infrutescens per plant, of fruits per infrutescence, and of seeds per fruit was determined in 50 randomly chosen plants. Finally, the average number of seeds per category was estimated. Due to the small size of seeds and to the disruptive effects of cattle, transitions from seeds to seedlings had to be estimated, dividing the number of seedlings registered along transects between the number of individuals in the reproductive categories. The number of seedlings from each category was determined proportionally, according to the number of seeds produced by each one.

The transition matrix was iterated multiplying it by the vector that represents the population structure at time $t_1, t_2, \ldots t_n$, until the population structure stabilized, and the population finite growth rate (λ) was calculated (Caswell 2001). Elasticity was calculated in order to identify the proportional contribution of each transition to the finite growth rate (de Kroon et al. 1986). Elasticity was calculated as:

$$e_{ij} = (a_{ij}/\lambda) \times s_{ij}$$

where

e_{ij} elasticity

a_{ij} transition from ith to jth category

λ finite growth rate

s_{ij} $\delta\lambda\delta \mathrm{a}_{ij}$ = sensitivity

(de Kroon et al. 1986; Caswell 1989).

11.3 Results

11.3.1 Dynamics of Sinkholes

When first censed, 121 sinkholes were registered. Thirty-one new sinkholes were formed between January 2008 and January 2009 (i.e., a total of 151 sinkholes were

Table 11.3 Percentage of sinkholes with and without water (January 2008–January 2009)

	Jan 2008	Mar	May	Jul	Sept	Nov	Jan 2009
With water	50.79	26.19	5.88	9.42	19.59	26.62	44.6
Without water	49.21	73.81	94.12	90.6	80.41	72.85	54.6

sampled during this period). Except in March, new sinkholes were registered in every sampling period. May and September showed more new sinkholes (12 and 10, respectively), while only two new ones were found in July and three in January 2009. During the extremely warm summer months, fewer sinkholes had water in their interior (Table 11.3). Throughout 2012, almost no water was registered in the sinkholes (M. Rodríguez-Sánchez, pers. com) .

Most sinkholes were colonized by plants, and some showed high cover percentages, while some lacked vegetation, especially if they were newly formed. Most (but not all) of the newly formed sinkholes were colonized as time passed. The lowest percentage of colonized sinkholes was registered in July (93.5 %), and the highest in November (97.4 %).

The size structure of the group of sinkholes, considered all together, is defined by the percentage of each category in the group. More than half of the sinkholes remain in the same size category after 1 year, but the size of 137 sinkholes belonging to different categories increased enough to move the sinkholes to bigger size categories. Sinkholes have a very dynamic behavior throughout the year, as can be seen in Fig. 11.4.

Iteration of the annual transition matrix leads to a projection of how sinkholes will behave if environmental conditions remain constant (Caswell 2001; Gotelli 2008) (Fig. 11.5). According to this model, sinkholes will become constantly larger, and most of them will reach category seven in the next 10 to 13 years.

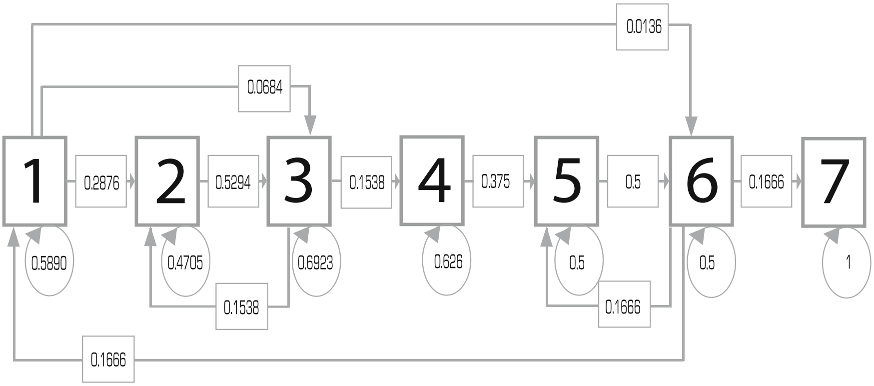

Fig. 11.4 Annual transition probabilities for sinkholes categorized by size (area). Thicker lines show the most important transitions that include growth from categories 2 to 3 and 5 to 6, and permanence in most categories. Categories: *1* = 0.003–0.05 m^2; *2* = 0.051–0.1 m^2; *3* = 0.11–0.2 m^2; *4* = 0.21–0.4 m^2; *5* = 0.41–0.6 m^2; *6* = 0.61–1.6; *7* m^2 = more than 1.6 m^2

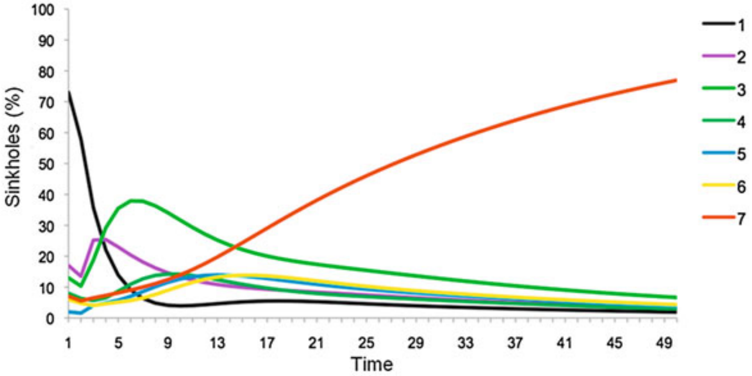

Fig. 11.5 Projected size structure of sinkholes in the Churince system, based on 50 iterations of an annual transition matrix. Categories: *1* = 0.003–0.05 m^2; *2* = 0.051–0.1 m^2; *3* = 0.11–0.2 m^2; *4* = 0.21–0.4 m^2; *5* = 0.41–0.6 m^2; *6* = 0.61–1.6; m^2, *7* = more than 1.6 m^2

Sinkholes in category seven showed no retrogression, which might lead to an overestimation of their importance in the dynamics of the system in our model. Existing small sinkholes will increase in size, but the smaller categories will not disappear completely because new sinkholes will keep forming constantly.

11.3.2 Population Dynamics of S. Ebracteatus

S. ebracteatus was registered in most of the sinkholes (growing on the bottom, the walls and the borders), as well as in the flatland that surrounds them. It can also be found close to many of the water bodies throughout Cuatrociénegas, among a few other perennial species that include *Flaveria chlorifolia* (Asteraceae), *Bolboschoenus maritimus* (Cyperaceae), *Jouvea pilosa* (Poaceae), and the annuals *Sabatia tuberculata* (Gentianaceae) and *Eustoma exaltatum* (Gentianaceae). Among these species, the most common colonizers of newly formed sinkholes are *B. maritimus* and *S. ebracteatus*, the latter being the most frequent. None of the species are exclusive of sinkholes, as they can also be found in the borders of (or close to) water bodies, and except *for B. maritimus*, in the flatland at the end of the Churince System (Pérez y Sosa 2009).

S. ebracteatus was found in 65.4 % of the sinkholes in January 2008 and, by January 2009, it had germinated and/or established in 79.9 % of them. It is the most frequent species in the sinkholes. Together with *B. maritimus*, *S. ebracteatus* was consistently the first species to establish in newly formed sinkholes, the latter being significantly more frequent than the former (Pérez y Sosa 2009). *S. ebracteatus* was registered in most of the new sinkholes formed during the study period. However, once other species start establishing, the relative cover and importance of *S. ebracteatus* becomes progressively lower (Pérez y Sosa 2009).

In the Churince system, *S. ebracteatus* forms tight clumps, with a falanx type growth (Lovett-Doust 1981) and usually short horizontal and vertical internodes. When resources are depleted in a specific part, growth is resumed in other directions. Sometimes a clear fairy-ring pattern of resource depletion and growth can be seen. Frequently, small monticules are formed where this species grows, especially in the flatlands. These monticles are part of the landscape in our study site. Reproduction starts in plants belonging to category 3, and persists in the following categories. Flowering starts in March, and fruits are produced from May to September. Senile seedless fruits can remain attached to the plant for many months. On average, each infrutescence has 4.6 fruits, and each fruit has 31 seeds. The average number of seeds per category is shown in Table 11.4.

The structure of the population changed through time during the study period. The life cycle of this species is complex and it includes growth, retrogressions (i.e., transitions to lower size categories) due both to cloning and to the loss of green rosettes, and permanence in the same category for periods of variable length (Fig. 11.6). Clones, which can easily be identified as new individuals with only one well-developed rosette, are produced throughout the year, but are more frequently formed during the warm season. The finite population growth in this time interval was $\lambda = 0.8561$ (i.e., the population decreased about 15 % in this part of the Churince system during the period considered in this study).

The elasticity matrix, shown together with the transition matrix in Table 11.5, shows that the most relevant process for the finite population growth rate is the permanence of category 6, followed by permanence of category 5 and by the transition from five to six. The lowest values concentrate in the first categories, and the low elasticity value for the transition from seedlings to subsequent categories indicates low recruitment rates, with a low contribution to the growth of the population.

Table 11.4 Estimated number of seeds produced by each category

Category	Total number of individuals (June 2008)	Estimated number of seeds/individual (June 2008)
1	3	0
2	23	0
3	84	195.5
4	105	204.9
5	178	416.8
6	139	493.0
7	61	550.1
8	57	514.2

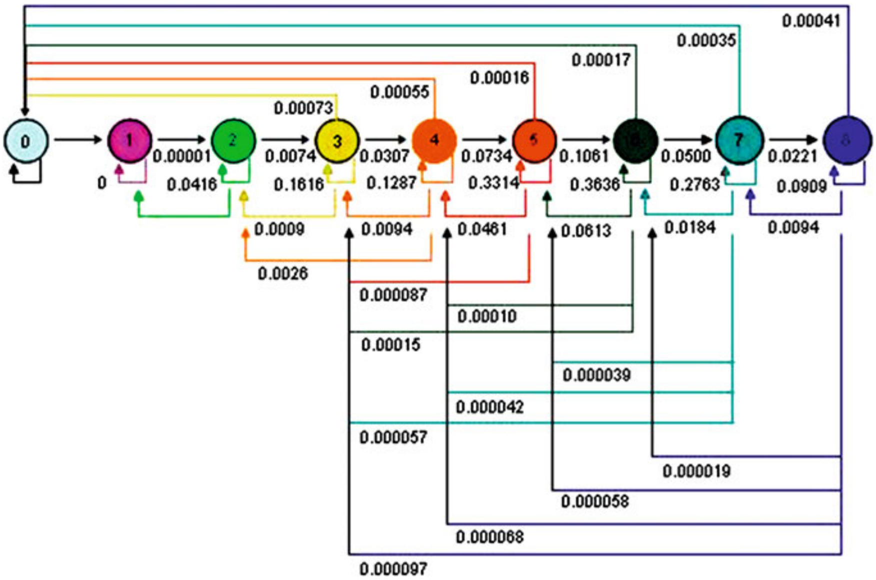

Fig. 11.6 Life cycle diagram of *S. ebracteatus*, showing growth, retrogression and permanence probabilities from March 2008 to March 2009. Arrows show the direction of transitions, values show their probabilities. Reproduction and clonation start in stage three. Permanence takes place in all stages. Numbers in circles indicate plant categories

11.4 Discussion and Conclusions

Sinkholes of different sizes will probably continue to form as long as water continues to flow from Río Churince towards the flatland that surrounds it, due to an unstable underground system. This process is related to the decrease in water flow from Poza Churince, which is associated with a general loss of water in the underground systems in the Cuatrociénegas and surrounding valleys. If the conditions we experienced during our study persist through time, the remaining water bodies of the Churince system will be surrounded by big soil depressions colonized by species that take advantage of humidity and can tolerate high salinity levels. In other words, the loss of water from the stream and the resulting formation of sinkholes will eventually transform this area into a set of big depressions, and the soil will collapse repeatedly and constantly. However, the process of sinkhole formation could decrease progressively if the different parts of the system continue to dry, vegetation in the sinkholes will eventually die, and a set of salty depressions will become the dominant landscape around the dry water bodies.

The population dynamics of colonizing species is affected both by miscrosite conditions (Pickett and White 1985; Montaña 1992; Vega and Montaña 2004; Millar and Chesson 2009) and by the stochastic variation of some of the climatic and microclimatic parameters (Knox 1995; Golubov et al. 1999). Only seven

Table 11.5 Annual transition (**a**) and elasticity (**b**) matrices of *S. ebracteatus* (March 2008–March 2009)

Category	1	2	3	4	5	6	7	8
(a) *Annual transition*								
1	0	0	0.0007	0.0005	0.0001	0.0001	0.0003	0.0004
2	0.0357	0.04166	0.0001	0.0099	0	0	0	0
3	0.1428	0.2500	0.1616	0.0693	0.0730	0.0909	0.0789	0.1904
4	0.2857	0.2083	0.2727	0.1287	0.1573	0.0584	0.0921	0.1190
5	0.0357	0.1666	0.1919	0.3960	0.3314	0.2272	0.1184	0.1309
6	0.0357	0.0416	0.0707	0.099	0.2528	0.3636	0.1578	0.0833
7	0.0357	0	0	0.0198	0.0112	0.1623	0.2763	0.1190
8	0.0357	0	0	0	0.0224	0.0584	0.2105	0.3095
(b) *Elasticity*								
1	0	0	5.859E-05	6.0365E-05	3.4869E-0	3.0605E-05	2.4263E-05	2.1985E-05
2	1.1007E-05	6.32966E-05	0	0.0012	0	0	0	0
3	4.5555E-05	0.0003	0.0151	0.0088	0.0186	0.0188	0.0063	0.0121
4	0.0001	0.0003	0.0290	0.0187	0.0455	0.0137	0.0083	0.0085
5	1.5785E-05	0.0003	0.0249	0.0703	0.1172	0.0651	0.0131	0.0115
6	1.9052E-05	0.0001	0.0111	0.0212	0.1079	0.1258	0.0212	0.0088
7	1.8368E-05	0	0	0.0040	0.0046	0.0541	0.0357	0.0122
8	1.7477E-05	0	0	0	0.0088	0.0185	0.0259	0.0301

First line = fecundity; diagonal = permanence; below-diagonal = growth; above diagonal (except first line) = retrogression. Highest three values are shown in bold characters species colonized these sinkholes and established in them, and almost nothing is known about them.

According to our results, *S. ebracteatus* is a frequent and abundant species in the study site, and is one of the first species to colonize new sinkholes. Its complicated life cycle includes the production of sexual and vegetative propagules that allow the colonization of microsites through new genotypes and with those that have already proven to be successful. The contribution to population growth of fecundity is extremely low, and it is probably affected by low germination and establishment opportunities, as well as by cattle, which eat inflorescences, reducing seed production, and trample small plants. Low seedling survival explains the low elasticity values that characterize the transition from categories 1 and 2 to subsequent categories. It is common to find the highest elasticity values in the permanence of the last stages of perennial plants (Silvertown et al. 1993; Godínez-Alvarez et al. 2003). In this population, permanence in the last four categories, as well as the transition from category five to six make a major relative contribution to the finite growth rate of the population. This indicates that once an individual is successfully established it will grow as much as possible and will remain in a specific microsite, foraging short-distance neighboring safe sites and colonizing them through vegetative growth. Seeds will germinate under specific environmental and physiological conditions after short- and long-distance dispersal. However, under average conditions, the population will persist because it can withstand selective pressures caused by the dynamic environmental changes the region is undergoing. Thus, permanence in the last four categories allows the population to persist, to grow vegetatively, and to have new genotypes produced.

Based on the growth form and the population dynamics of *S. ebracteatus,* we propose that this species can be considered an indicator of humid habitats, and their variations, and the behavior of the population can be regarded as an indicator of water availability. An increasing abundance and density of this species, especially in areas that are relatively far from the water bodies whose borders are their natural habitats, indicates a higher availability of humid microhabitats. Population growth rates vary through time, but constant changes of the population’s finite rate of increase can indicate an increase of water loss from the water bodies or the loss of humid microhabitats due to their final desiccation, or to the recovery of the water conditions that prevailed before disturbance.

The local population of *S. ebracteatus* in our limited study area is being affected by the general loss of water this system is undergoing, but further and more detailed studies are needed before assessing this with certainty. This growth rate might also be, if the latter hypothesis is confirmed, a warning sign of water loss. The plasticity of this plant allows it to grow moving onwards to higher categories, to remain for long periods in the same category and to have retrogressions due both to negative growth (loss of green rosettes) or to the production of new physiologically independent individuals (i.e., clones). Further information on the physical characteristics of the sinkholes, such as humidity, temperature, and pH of the water, as well as their behavior in time, is needed to properly explain the characteristics of these microhabitats, how they behave seasonally, and how and why they are changing.

It is possible to assume that the general destabilization of the water system due to overexploitation of the aquifer (CONAGUA 1988) and a locally induced drought could transform the riparian habitats into physically unstable, dry, and extremely saline depressions. The loss of Laguna Churince and, eventually, of all the Churince system could have a long-term, deep effect on the general ecosystem structure and function. This could affect the valley through the loss of valuable ecosystem services it provides, including recharge of aquifers, the maintenance of habitat and specific biodiversity, as well as cultural and aesthetic values.

The extremely valuable water of this arid region in Mexico has been overexploited for a long time (CONAGUA 1988) and it is very difficult to separate it from the generalized loss of water the wetlands of the Cuatrociénegas Valley are suffering. Despite the efforts of numerous stakeholders, ecosystem services of all types, particularly those related to water, are being irreversibly lost due to the lack of effective environmental education, compliance with laws and regulations, long-term public policies, and adequate supervision—all related to powerful economic interests. Preventive measures need to be taken immediately, as there is a severe collapse of the system we are studying, and this could be happening in other parts of this area of ecological and environmental importance.

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Chapter 12
The River Murray-Darling Basin: Ecosystem Response to Drought and Climate Change

Ian C. Overton and Tanya M. Doody

Abstract The River Murray-Darling Basin is one of Australia's largest river basins, and contains highly valued water-dependent ecosystems, including 16 Ramsar-listed wetlands. Through the impact of drought and over-allocation (69 % of the basin's water is abstracted for irrigation, industrial, and domestic use), these ecosystems are now widely considered to be severely degraded. Future climate scenarios suggest a drier and more variable climate with continued and intensified drought periods. Future water-sharing policies are under consideration to address this degradation by changing the balance between consumptive and environmental water, including the security of environmental water. This chapter outlines the challenges involved in managing ecosystem adaption to a drier climate while maintaining key ecosystem assets. We conclude that it is unlikely that it will ever be possible to return to an ecosystem like what existed pre-irrigation development. While this past ecosystem state has often been used as benchmark in ecological assessment, the great scientific challenge now is to provide rigorous assessment that allows those setting policy to gain a better sense of what is ecologically possible and socially desirable within constraints of water diversion and climate futures that we now face.

12.1 Introduction

Australia has a diverse range of environments from tropical rainforests to arid deserts. The spatial distribution of these ecosystems is, in part, driven by the large differences in rainfall patterns. Drought conditions across much of Southern Australia over the last decade and provision of freshwater for human development at an increasing rate over time, is now leading to a decline in water-dependent

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ecosystems (Garrick et al. 2009). The River Murray-Darling Basin has a long history of water resource development by installing weirs which control flow for navigation and construction of headwater reservoirs to provide downstream irrigation water supply from the 1920s onwards. Such water resource development changes the seasonality of flows, and medium and small floods have largely been removed from the flow regime. In areas downstream of irrigation areas, the mean annual flow has been reduced. This change in the flow regime and overall decline in available environmental water reduces wetland connectivity and riparian zone flooding frequency (Ralph and Rogers 2010; Jolly et al. 1993). A consequence is potentially compromised resilience of floodplains (Colloff and Baldwin 2010).

Despite a gradual and continuous growth in extraction, it is only recently that the most significant decline has been seen in aquatic ecosystem areas such as the River Murray-Darling Basin,, southwestern Australia, and southeastern Queensland (Connor et al. 2009; Pittock and Connell 2010; Neville 2009; CSIRO 2008). This is because much of the expansion in water resource development occurred during periods of above-average rainfall from the 1950 to 2000. The recent decade (2000–2010) of drought in Australia has shown that the degree of water licensing for diversion has exceeded sustainable limits consistent with maintaining environmental health. The combined impact of expanded extraction rates and drought in the last decade has driven many ecosystems to the brink of collapse. For example, riparian forests of 300-year-old trees have survived previous drought periods; however, these forests are now severely stressed (Fig. 12.1) with only 30 % of river red gum in good condition along the Victorian River Murray floodplain (Cunningham et al. 2009).

One primary impact of future climate change is likely to be on water and rivers, as the magnitude, timing, frequency, duration, and variability of the different components of flow regimes in river basins worldwide is altered, as indicated in recent hydrologic modeling research, for example, Marcarelli et al. (2010) in the United States; Strom et al. (2011) in Sweden; and Acuna (2010) in Spain. The combination of these impacts erodes the self-repairing capacity of ecosystems until they cease to cope with sudden changes (Barchiesi et al. 2009). For the River Murray, future climate scenarios suggest a drier and more variable climate with continued and intensified drought periods (Kirby et al. Chap. 16). The c-mid (2 °C warming by 2030) climate change scenarios for the basin suggest a reduction of 15 % in available water, resulting from higher average temperatures, greater potential evapotranspiration, and lower mean rainfall. This reduced water availability would result in additional stress on the basin environment from less flooding and more River Murray Mouth closures (CSIRO 2008; Crosbie et al. 2010; Bryan et al. 2011; Austin et al. 2010).

This chapter describes the ecological assets of the River Murray-Darling Basin and the recent rapid changes in the condition of the ecology of the riverine environment within the River Murray-Darling Basin, due to high levels of extraction and drought. It also outlines approaches that have historically been used to manage system ecological assets, and potential future approaches to manage

Fig. 12.1 River *red gum* (*Eucalyptus camaldulensis*) in healthy condition and degraded as a result of drought impacts

environmental health across the basin in a sustainable way, with water availability increasingly limited in droughts under climate change.

12.2 The River Murray-Darling Basin Water-Dependent Ecosystems

The River Murray-Darling Basin is Australia's largest river basin, with an area of more than 1 million km^2, covering one-seventh of Australia (Fig. 12.2). It contains Australia's three largest rivers: the River Murray, the Darling River, and the Murrumbidgee River. Irrigation in the basin accounts for 70 % of Australia's irrigated crops and pastures, and it is home to more than 2 million people (Connor et al. 2009). Irrigated produce includes dairy, rice, cotton, beef, fruit, vegetables, and fiber. In 2004–2005, the agriculture industry extracted 83 % of the total water available (ABS 2010).

The Darling Basin drainage area encompasses an area of approximately 640,000 km^2 and ends at the confluence of the Darling River with the River Murray. The region is characterized by many terminal wetlands. Australian rivers in this drainage area have the most variable flow regimes in the world (Puckeridge et al. 1998) with periods of zero flow in most rivers extending to months and years

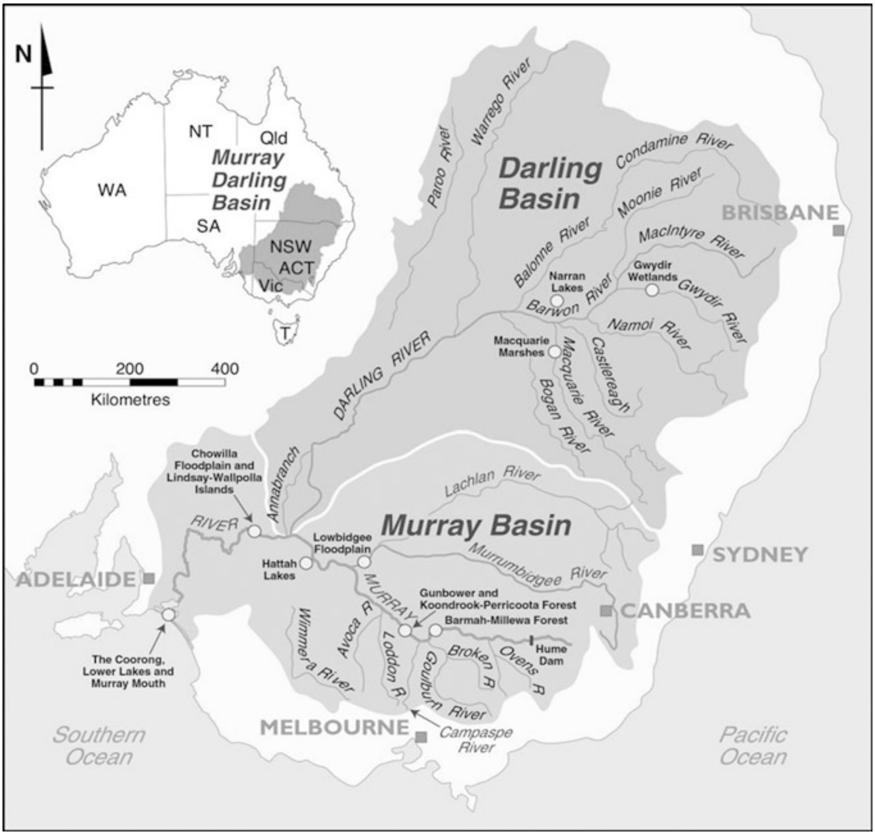

Fig. 12.2 Location of the River Murray-Darling Basin within Australia showing the major rivers and key environmental assets (reproduced with permission from Saintilan and Overton 2010)

in the drier parts. Northern rivers generally flood in the summer from monsoonal rains, while the unregulated portions of southern rivers generally have high river flows from winter, extending to the following autumn. Rivers in the Darling Basin are less regulated than the southern rivers, with many (such as the Paroo and Warrego) having their flow regimes relatively unchanged from pre-European settlement.

The basin is home to many wetlands, including the Macquarie Marshes, the Gwydir Wetlands, the Narran Lakes, and the Paroo Wetlands (Fig. 12.2), all of which are listed as Ramsar wetlands of international significance.

The Murray Basin is the drainage area of the River Murray and is connected to rivers, such as the Murrumbidgee and the Lachlan from the north, and the Ovens, Broken, Goulburn, Loddon, and the Avoca from the south. The basin is defined by the River Murray, which is 2,375 km in length, and begins in the Australian Alps and ends at the Murray Mouth, draining into the southern ocean in South Australia, with an annual average discharge of approximately 24,000 Gl/year. The Murray

Basin is approximately 430,000 km^2, with much less variability in runoff than the Darling Basin. Annual flow variability ranges from 30 to 300 % of the long-term mean. Unregulated flows peak in spring as the snow melts and are at a minimum in mid-autumn. While most rivers are highly regulated in the Murray Basin, the Ovens River remains the most unregulated of the major rivers.

Environmental assets of the River Murray-Darling Basin are protected by international agreements, such as the Ramsar convention for wetlands of international importance (10 wetlands in the basin); bilateral migratory bird agreements, such as the Japan Australia Migratory Bird Agreement (JAMBA); as well as similar agreements with China (CAMBA) and the Republic of Korea (RO-KAMBA). Murray Basin wetlands of international and national significance include the Barmah-Millewa Forest, the Chowilla Floodplain and Lindsay and Wallpolla Islands, Banrock Wetlands, and the Coorong and Murray Mouth, all of which are listed as Ramsar wetlands. Other wetlands of importance are identified though the River Murray-Darling Basin Living Murray Program and include the Gunbower-Perricoota Floodplain, the Hattah Lakes Wetlands and the River Murray Channel (Fig. 12.2) (MDBC 2005). Additional important wetlands include the Lower Murrumbidgee and Great Cumbung Swamp.

Australia's national reserve system coordinates protection of natural areas. Of the 85 eco-regions identified in Australia, many occur within the River Murray-Darling Basin (DEWHA 2010). The principles that underpin the national reserve system include comprehensiveness, adequacy and representativeness (CAR). These terms have been defined by the Australian and New Zealand Environment and Conservation Council (ANZECC 1999) as:

- comprehensiveness—inclusion of the full range of ecosystems recognized at an appropriate scale within and across each bioregion;
- adequacy—maintenance of ecological viability and integrity of populations, species and communities; and
- representativeness—areas selected for inclusion in reserves should reasonably reflect the biotic diversity of the ecosystems from which they were derived.

In addition to using the scientifically based CAR criteria, spectacular landforms and scenery as well as natural areas of high public use are also commonly included in parks and reserves. The main priority for the National Reserve System is to address gaps in comprehensiveness at the national scale. Australia is working towards a target of 10 % of our bioregions to be part of the National Reserve System. Protection of ecosystems is undertaken in areas that are currently poorly reserved (less than 10 %) or not protected at all. A secondary priority is to conserve:

- key habitats for nationally listed threatened species or migratory species and/or Ramsar sites or wetlands of national importance; and
- areas that contribute to whole-of-landscape conservation outcomes, such as places that offer refuge or contribute to the adaptation of biodiversity to a changing climate.

Those habitats within the River Murray-Darling Basin range from less than 15 % to most being less than 5 % represented. Reserves include national parks, nature reserves, Ramsar-listed wetlands, and wetlands of national importance.

12.3 Historical Flow Regime Changes and Ecological Impacts

Flow regimes in the River Murray-Darling Basin have changed significantly since pre-European settlement with the development of water regulation and extraction. Norris et al. (2001) reported that 40 % of the river length assessed in the River Murray-Darling Basin had biota that was significantly impaired, and 95 % had degraded environmental condition with 30 % substantially modified from the original condition. More than half of the reaches assessed had altered hydrology, with the greatest changes immediately downstream of dams and in lowland reaches used for irrigation. The most recent sustainable rivers audit (MDBC 2008a) reported riverine health in the River Murray-Darling Basin. Of 23 valleys, one was reported as being in good condition (the Paroo), two in moderate condition, seven in poor condition, and 13 in very poor condition. The River Murray-Darling Basin Commission reported on the condition of the six iconic sites along the River Murray (MDBC 2008b). Few waterbirds were present and the majority of floodplain wetlands were dry. The dominant floodplain communities of river red gum (*Eucalyptus camaldulensis*) and black box (*Eucalyptus largiflorens*) were in decline, and understory vegetation diversity was reduced (MDBC 2008b). A similar pattern of decline was evident in the Ramsar-listed wetlands of the Darling Basin. At Narran Lakes, approximately half of the river red gum and river cooba (*Acacia stenophylla*) had died in 2007 (Thoms et al. 2007). The central part of the wetland of the Macquarie Marshes has seen the loss of approximately three-quarters of the Cumbungi (*Typha* Spp.) and water couch (*Paspalum distichum*) community over 10 years, replaced by invasion of drought-tolerant chenopod shrubs (Bowen and Simpson 2009). Three-quarters of the water couch/spike rush association and more than half of the *Bulbochenus* were lost between 1996 and 2005 from the Gwydir wetlands (Bowen and Simpson 2009).

Annual average flows at the Murray Mouth has been reduced by more than 60 %, from the average level prior to river regulation, with flow ceasing at the mouth 40 % of the time, an increase from 1 % under natural conditions (CSIRO 2008). As a result, the Coorong, an end of system brackish estuary, has become hypersaline and is in danger of irreversible change (Webster et al. 2009).

Floods in the lower River Murray in South Australia have decreased by a factor of between two and three, since regulation in the 1920s (Ohlmeyer 1991). Areas that were likely to flood once every 2 years prior to development were then receiving floods once every 6 years. In the period from 1999 to 2010, no flooding has occurred in the lower River Murray. By comparing the current frequency of floods with past periods, it is possible to assess the environmental stress across

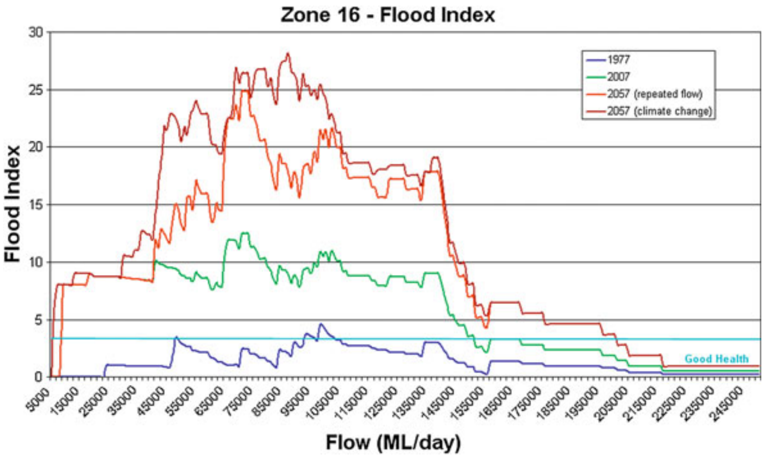

Fig. 12.3 Flood index for different river flows for zone 16 at Chowilla in the lower River Murray (Overton and Doody 2008). Good health can be attributed to an index below the *light blue line*

flow regimes. Flood index for four flow scenarios at Chowilla are shown in Fig. 12.3. The flood index represented is the ratio of current flood return periods to natural flood return periods. If areas receive floods no less than three times their natural interval (flood index of three or less) their health has been shown to be generally in good condition (Overton and Doody 2008). In Fig. 12.3, 1977 illustrates flood index values for a period of good flows; 2007 shows a drought period after 7 years of low flow; 2,057 models repeated flows similar to the last 50 years, and 2,057 modeled flows under a climate change scenario. In 2007, most of the floodplain has an index value above three, and the environmental condition displays commensurate stress. Future predictions (2,057, repeated flow and climate change) show a significantly altered flood regime that most likely would not support the current ecology.

Vegetation in the lower River Murray, for example, has been experiencing severe stress as a result of drought and salinity. River red gum trees are in especially poor health as noted by Cunningham et al. (2009), and many have died while black box and river cooba have a higher tolerance to reduced water availability. This is a result of adaptations of the unique sclerophyllous Australian vegetation. River red gums, for example, have a requirement for a one to two yearly flood return interval and as such are located within the rivers flushed zone, as opposed to black box and river cooba, which are located at higher elevations. It has been noted by Hatton and Wu (1995) that when water stressed, eucalypts will undergo rapid leaf loss to reduce tree water requirement. It is likely that they will also maintain a much higher sapwood area for a prolonged time, in order to respond rapidly when water becomes available (Doody and Overton 2009). Research indicates that river red gum and black box are opportunistic water users that can access a variety of water sources, such as stored-soil water, rainfall, fresh-flushed river banks (Thorburn et al. 1993; Mensforth et al. 1994; Overton and

Table 12.1 Area of floodplain in good health (flood index less than or equal to three) under different flow regimes (reproduced with permission from Overton and Doody 2008)

Area (ha)	1977	2007	2,057 Flow repeated	2,057 Climate change
Healthy river (index <= 3)	598,000 92 %	260,000 40 %	247,000 38 %	221,000 34 %

Jolly 2004; Holland et al. 2006) and deep groundwater, using deep sinker or tap roots (Bren 1991). Leaves are hard and shiny with waxy cuticles that reflect heat and reduce water loss. Black box and river cooba appear to have very strong stomatal controls over water loss, with substantially higher water use when water was readily available. This is compared to a water-limited environment, with a 76 and 98 % reduction in daily water use, respectively (Doody et al. 2009). Recruitment of the riparian forests and woodlands has been low for many years, due to a reduction in flooding frequencies, leaving 300-year-old riparian areas with few or no cohorts.

Table 12.1 indicates the area of healthy floodplain along the River Murray, with an index less than or equal to three for each scenario shown in Fig. 12.3. Table 12.1 hydrograph data shows that 52 % of the floodplain that did flood 1 year in three, in 1977, did not flood at least once every 3 years in 2007. Predictions of further decreases in area inundated once every 3 years are also shown for the climate scenarios. The decline in flood index has been mirrored with a decline in actual floodplain condition at areas such as Chowilla and the Lindsay-Wallpolla icon site (Overton and Doody 2008).

12.4 Active Floodplain as New Concept for Ecological Flow Management

An important idea for ecological flow management, related to the flood return index, is the concept of an “active floodplain.” This concept describes a flood plain area where a flood frequency return period can support a healthy floodplain ecosystem, and above which the environment of the area’s terrestrial ecosystem changes to a new state. The extent of floodplain inundated from 2000 to 2009 provides an indicator of current active floodplain areas within the River Murray-Darling Basin. Figure 12.4 highlights the extent of flooding during a 10-year period from 1984 to 1993, compared to flooding in a 10-year period from 2000 to 2009 years. Over the period from 1984 to 1993, 76 % of 6 million hectares of floodplain were inundated (~4,550,000 ha), compared to only 25 % (~1,500,000 ha) in the 10 years from 2000 to 2009 (Overton et al. 2010a, b). Again, this decline in flood inundation is reflected in a decline in floodplain condition from 2000 to 2009.

Figure 12.5 conceptually illustrates the extent of the current active floodplain (return interval of one in 10 years) against the old active floodplain extent.

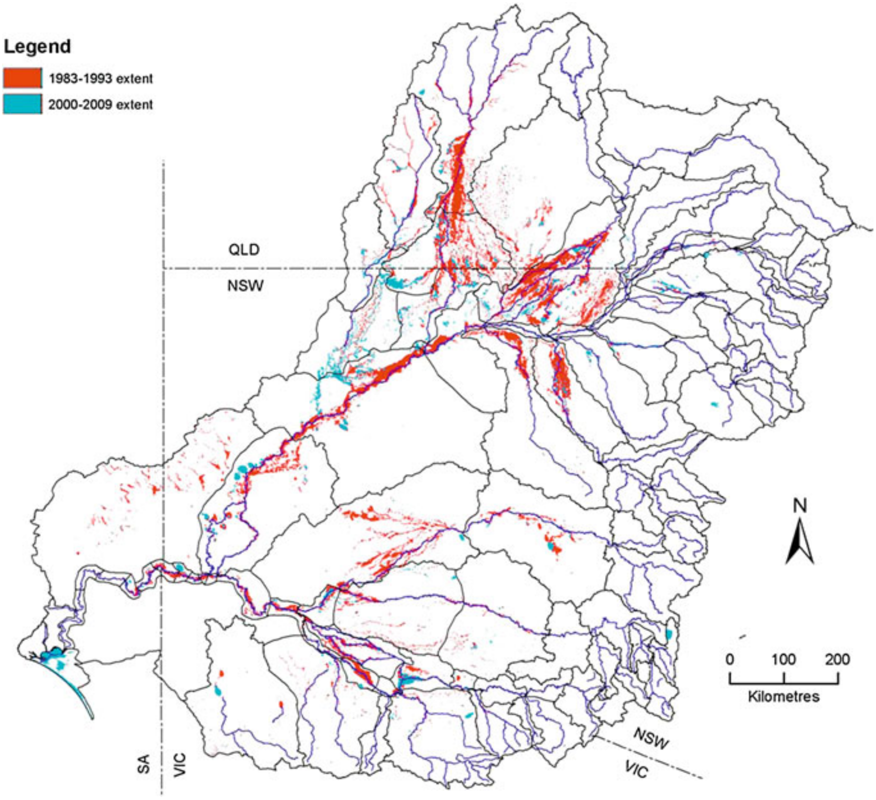

Fig. 12.4 The change in the area of floodplain inundation in the River Murray-Darling Basin during a 10-year period from 1984–1993 to 2000–2009 (reproduced with permission from Overton et al. 2010a, b)

A similar comparison is the change in flood inundation area between the two flood extents shown in Fig. 12.4, representing two different one in 10 flood return periods. In Fig. 12.5, the presence of 300-year-old floodplain trees indicates the floodplain extent. Many of these trees are now dying or dead.

A shift in the flooding frequency to lower-elevation areas means that the vegetation must reposition to stay in its preferred habitat. The potential relocation of vegetation to new areas with the required hydrological parameters can only occur where suitable soil types allow. Areas now exist on the River Murray floodplain where this relocation is occurring. Figure 12.6 illustrates the regeneration of new river red gum trees to a lower elevation with a more frequent flood return interval than the old river red gums in poor health situated higher on the floodplain. Such recruitment has been considered invasive in the past, leading to removal; however, in 2010, these trees are being considered representative of new habitat areas suitable to sustain these trees. This ecological adaption to environmental change can be supported through management in regions where more

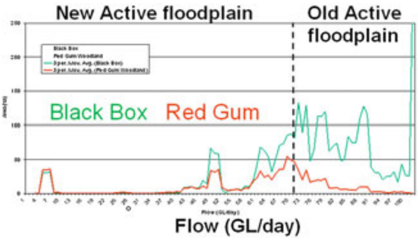

Fig. 12.5 The areal distribution of riparian forest trees across the floodplain, based on River Murray discharge. The *vertical dashed line* represents the current flooding frequency of one in 13 years. This frequency is used to represent the 150 Gl/day flow. The shift in old active floodplain to new active floodplain is illustrated (reproduced with permission from Overton and Jolly 2004)

Fig. 12.6 River *red gum* establishing in lower parts of the floodplain next to old, but poor, trees on higher ground with less flooding frequency

natural flow regimes cannot be reinstated due to resource limitations. Even with a new flow regime, there will still be a range of floodplain habitats similar to those found under pre-development conditions but in smaller spatial extent. This adaptation of the floodplain to different flow regimes, however, involves decline and regeneration, and can take hundreds of years to restore a mature forest environment.

Not only have floodplain areas declined due to reduced flooding frequency but also fringing riparian areas that depend on lateral recharge of river water (losing creek system) have struggled to maintain health. These areas have been affected as a result of reduced frequency of bank full events. Figure 12.7 illustrates a significant difference in riparian health along a creek length separated by approximately 3 km. There can be large differences between losing versus gaining systems where saline groundwater discharges into the creek.

Fig. 12.7 The same creek on the River Murray floodplain showing the impacts of bank full flow in relation to regional groundwater levels. **a** Losing creek with fresh water recharging in the banks, **b** gaining creek with saline discharge under the fringing banks

Declining water availability can also result in a range of other threats to the environment (Bond et al. 2008) including:

- Increased presence of invasives, particularly terrestrial weeds, on floodplain areas as a result of reduced flooding;
- Decline in abundance and local extinction of aquatic taxa from small invertebrates to fish;
- Water stratification associated with higher temperatures leading to water quality issues;
- Reduction in suitable bird-breeding habitats related to flood magnitude and duration, as well as reductions in food sources as aquatic supplies diminish;
- Increased salinization of soils as a result of reduced flooding and increased evaporation rates from increased temperatures;
- Increased risk of water-quality issues, such as blue-green algal blooms as a result of low-flow conditions, as well as salinity and acidity from exposed acid sulphate soils;
- Depleting recharge of groundwater reserves;
- Reduced resilience of native fauna, including fish, invertebrate and bird species;
- Reduced resilience, abundance and diversity of aquatic plants; and

- Changes to the channel geomorphology, including bank stabilization and sedimentation issues.

12.5 Evolving Environmental Flow Policy

To some extent, environmental flow management has been a feature of the River Murray-Darling Basin system management for decades; however, the effectiveness of such flows has been limited by the proportion of water available as well as a lack of strategic purpose in many situations. For much of the early 1990s, the management of environmental water was "essentially ad hoc" (Walker et al. 1995) and as recently as 2000, environmental flow management could be described as being based on "best informed guesses" (Thoms et al. 2000).

Essentially, through most of the twentieth century, the focus of River Murray-Darling Basin policy and management was on extraction for economic development. The traditional management approach to environmental assets in the basin has been described as hoping that the ecosystem can survive on the flows that come in excess of water extraction licenses. Many authors suggest that the basin's ecological conditions have begun passing critical ecological health thresholds as a result of growing extractions over the past 10–15 years. This is shown conceptually in Fig. 12.8, which describes the relationship between the percentage of mean annual extraction, economic benefits of extraction and environmental benefits of leaving water for the environment (Barchiesi et al. 2009). The figure shows that beyond a critical extraction level, the cumulative benefits start to decline as the rate of environmental decline increases dramatically. Many authors have recently suggested that the River Murray-Darling Basin has recently passed that critical point. For example, during the recent drought in the lower lakes, many boat hire, fishing, food and accommodation business have suffered as a result of the environmental decline. Reduction in water levels of the lower lakes has led to exposure of large acid sulphate soil areas, which require mitigation with lime at further expense. As these costs increase, the value of a healthy ecosystem will in the future be seen more in monetary terms.

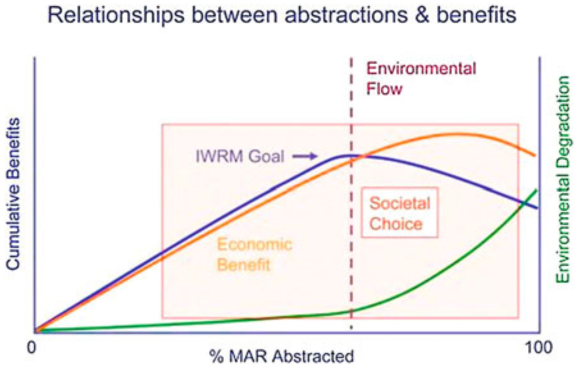

Fig. 12.8 Relationship between the percentage of mean annual runoff (abstraction) and economic and environmental benefits (reproduced with permission from Barchiesi et al. 2009). The goal of integrated water resource management (IWRM) is to maximize the cumulative benefit

Prior to the mid 1990s, a few substantive actions were taken to return flows to the environment. This could be for at least two reasons:

- The time lags in the system have meant that signs of decline have occurred many years after increases in extraction, so that the risks to ecological assets from reduced environmental flow were not easily recognized; and
- A period of increased water availability in the late twentieth century allowed higher extraction rates without great cost to the basin's ecological assets prior to the first decade of the twenty-first century.

As Commonwealth and state water management agencies began to recognize threats to ecological assets and ecosystem services at the close of the twentieth century and beginning of the twenty-first century, they began developing more extensive and comprehensive policy and management strategies to address the issue.

The National Water Initiative (NWI) is an Australian Commonwealth program, providing incentive for and benchmarking of states' to reform water policy (NWC 2009). Under this initiative, Australian, state and territory governments have made commitments to return currently over-allocated and overused groundwater and surface water systems to environmentally sustainable levels of extraction for irrigation and industrial use.

The NWI also has encouraged reforms that have lead to active water markets. As a result, the buying and selling of water license entitlements have grown rapidly over the last few years. Other chapters (Connor 2011) report this in more detail. These markets have provided the Australian government with an opportunity to reduce water extraction and restore environmental flows by buying-back water licenses. The first major buyback was under The Living Murray (TLM) Program of 2004. Buybacks continued and are scheduled to proceed into the future.

One critique of buybacks to date has been that many of the purchases have been low-security entitlements that have very low allocations in drought. Thus, they do not guarantee much more water in low-flow conditions. Another critique has been a lack of strategic spatial targeting in water buy-back.

Looking forward, water markets may be a useful mechanism for mitigating drought impacts on water dependent ecosystems. There is an opportunity for environment agencies, which now hold significant water entitlements, to trade in this annual water lease market, by purchasing environmental water in wetter seasons from irrigators who wanting to sell, in order to increase the peaks and durations of high flow events. Opportunities also may eventuate for environment agencies to sell some of their entitlements when in excess of desired ecological outcomes. The development of water trading is likely to grow closely with carbon and emissions trading. It also provides private non-profit organizations that are already using private donations to broker water for release into wetlands.

Such organizations are also interested in land purchases near rivers in the basin that often come with water entitlements, as a strategy to ensure appropriate land management along with return of water to the environment to ensure good conservation outcomes, although there are few examples to date.

The most significant recent reform related to the ecological health of the River Murray-Darling Basin is the Water Act (Australian Government 2007). This legislation established the River Murray-Darling Basin Authority (MDBA), a Commonwealth authority, with the mandate to develop and implement a basin plan, including an environmental watering plan and a water quality and salinity management plan. The Water Act represents a move away from a previous states priority in water management to a more federal approach.

Water-sharing plans previously developed by state jurisdictions will, upon their expiry, require Commonwealth endorsement for their renewal, providing a junction for a Commonwealth review of water-sharing arrangements, and conformity to objectives of a basin-wide environmental watering plan, which is likely to be one criterion for their acceptance (Saintilan and Overton 2010). It is expected that the new basin plan will represent the whole of the basin and all of its stakeholders and successfully address the over-allocation of water resources. This may mean that impacts of future droughts will be more evenly felt across use and localities within the basin, and water may be better managed in the interest of the basin as a whole rather than driven by state-based interests. Still-significant management changes remain in implementation of the plan.

12.6 Future Challenges in Ecological Flow Management

Environmental water planning traditionally takes a conservation and rehabilitation approach. In a system of changing water availability, through changes in water use or climate change, these traditional approaches restrict the flexibility required to support ecosystem adaptation within the bounds of desired environmental objectives. The drought of the early twenty-first century and the observed environmental degradation in the River Murray-Darling Basin has highlighted the issues of operating current plans within natural variability of climatic conditions, without incorporating strategies to maintain system ecological health with more extreme drought events. All evidence suggests that the current plans have contributed to environmental degradation by failing to address the security of environmental water, which was required to sustain ecosystems during the recent drought period, due to an over-allocation of water resources. Often past environmental watering plans did not set clear environmental objectives to guide water requirements under low-flow conditions adequately to provide flexibility for ecosystem adaptation.

A challenge going forward will be to develop environmental water plans that specify mechanisms for the provision of environmental flow for all river reaches within the basin, rather than concentrate only on iconic sites. Through planning for specific site-based assets and/or iconic species, there is a risk of impacting the integrity of the ecosystem. Current plans also do not fully combine surface water and groundwater as an integrated water source and as requirements for environmental watering. Adoption of a conservation planning theory approach in this process could be valuable, using the principles of comprehensiveness, adequacy, and representativeness (CAR) as part of the national reserve system. Currently, no uniform classification exists for water-dependent ecosystems in Australia, making representativeness difficult to measure. An initiative to map areas of high ecological value aquatic ecosystems (HEVAE) is underway, potentially supporting this process.

The Living Murray program established a list of environmental objectives, including the maintenance of 70 % of the existing area of river red gum. As the above changes to habitat indicate, a goal of maintaining existing areas will be difficult to achieve in a shifting climate. A challenge moving forward will be to manage the whole ecosystem in a basin to reduce additional degradation but also to allow transitions to work with changing water availability, while maintaining the integrity of the ecosystem (Barchiesi et al. 2009). One possible approach to achieve this would be to target the preservation of similar biodiversity, not necessarily in the same geographic location as before. This approach to an ecosystem objective was adopted in evaluation by Overton et al. (2010a, b) where optimization of infrastructure management was evaluated to produce similar hydrological habitat diversity to pre-regulation conditions in the Lower River Murray.

Another challenge is in the use of infrastructure installation, such as weirs and flood gates to complement environmental flow. Infrastructure has been used by water managers to create more desirable wetting and drying cycles in wetlands, often to provide refugia during drought periods. In some areas, low river flows have prevented wetland filling so artificial watering has been implemented by pumping water from river channels to ephemeral wetlands. However, concern exists with such engineering solutions as they do not provide the same fluid conditions as floods for nutrient cycling, seed production and juvenile establishment and persistence.

More fundamentally, there are challenges in developing a shared vision regarding the right societal balance between ecosystems that provide valued ecosystem services and economic returns from water resource development and political will, to implement such a vision. In 2004, The Wentworth Group released its “Blueprint for a National Water Plan” (Wentworth Group 2004), outlining solutions for protection and restoration of fresh water ecosystems, water conservation, and restoration of environmental flows to catchments such as the River Murray-Darling Basin. The blueprint indicated that solutions exist, but political courage was required to implement them. In 2008, The Wentworth Group and additional scientists put forward an interim basin plan as a model for accelerating water reform across the River Murray-Darling Basin to address the urgent provision of water to the Coorong and lower lakes in South Australia (Wentworth Group 2008).

12.7 Discussion and Recommendations

Society’s knowledge and priority on ecosystem protection has been an evolving process, and much of the degradation we reap today results from water and land development conducted decades ago, within the knowledge and value system of the time. Lag time between water reduction and ecosystem response can be quite long. We now know that the trajectory of basin ecosystem decline is significant, with many key wetlands and floodplains approaching a threshold point of no return. The change in habitat to a non-estuarine environment of the River Murray estuary is a real possibility with the Coorong changing to a hyper-saline lagoon. The recent drought illustrated that with past water-sharing rules, set in historically wet decades, little water is left for the environment when protracted drought occurs. The now-obvious stressed environmental state that resulted was not foreseen.

We are gaining the knowledge and now have the policy directive to undertake rehabilitation of the basin. Going forward with this will require valuing ecosystems so that trade-off decisions can be made. Whether this is through a common currency with agriculture or whether it is simply recognition of the importance of the intrinsic values and ecosystem services provided has yet to be resolved. Even with water reform and allocation of additional environmental water, the current starting condition will be a challenge. Elevated water tables, high salinity, senescing tree populations resulting from lack of recruitment over many years, and low population numbers all contribute to this challenge. This starting condition, and likely future climate change and drought are likely to drive further changes in the distribution of plant and animal species.

The newly enacted Water Act (2007) represents an opportunity to develop a more scientifically grounded strategy for environmental flow management, which is warranted given the levels of government investment in environmental water planned over the next decade (Saintilan and Overton 2010). This could include quantitatively based ecosystem response modeling of ecosystem responses under a range of management scenarios accounting for the confounding influence of climate change and considering surface water and groundwater, as well as variable and uncertain conditions. This can be underpinned by adequate monitoring of all water cycle components and consideration of the tradeoffs implied, accounting for costs of alternative water supplies for human uses.

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Part III
Hydrology and Water Resource Systems

Chapter 13
Drought Planning and Management in the Júcar River Basin, Spain

Joaquin Andreu, Javier Ferrer-Polo, M. Angel Pérez, Abel Solera and Javier Paredes-Arquiola

Abstract In the Júcar River Basin, water scarcity and hydrological variability produce frequent and long hydrological droughts. Preparation for droughts is achieved through (a) integrated river basin planning, including proactive measures that minimize the risk of operative droughts (i.e., failure of the system to provide water services); (b) special drought plans, including continuous monitoring of drought indexes in order to detect the risk in medium- to short-term management, and sets of proactive and reactive measures for different scenarios (i.e., normal, pre-alert, alert, and emergency); and (c) participatory drought management by means of a special drought committee, to mitigate the impact of droughts and find suitable compromise solutions to provide an equilibrium between economic sectors needs and environmental protection. We will illustrate how these three processes were applied in the recent 2005/2008 drought, and highlight the importance of up-to-date integrative decision support systems in enhancing and facilitating our ability to address drought.

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13.1 Introduction

The administration of water in Spain has been performed at the basin scale by the basin agencies (Confederaciones Hidrograficas) since 1926. Most watersheds controlled by these agencies in eastern and southeastern Spain can be classified as semi-arid or arid. Water usage in these regions is very intense, with ratios of water abstractions to renewable resources frequently close to one and, in some instances, greater than one, involving water reuse, aquifer overexploitation, or water imports from other basins (Table 13.1). This is a very simple and meaningful indicator of basin water scarcity, showing that it is pervasive in these basins, reaching the conditions of high water stress. A detailed review of most aspects associated with water in Spain is provided in a report prepared by the Ministry of Environment (MMA 2000).

Another distinctive characteristic of these basins is large temporal and spatial variability of precipitation and river flows. Hence, droughts are frequent, and water resource systems planning and management must be done with emphasis on drought preparation and mitigation.

Within this framework of scarcity and drought, it is necessary to develop proactive measures of basin management to minimize the potential consequences. Therefore, water laws were enacted to enforce the design and implementation of Basin Plans (BP), in 1985, and of Special Drought awareness and mitigation Plans (SDP) at basin and local scales, in 2000. BPs were approved in 1998, and SDPs were approved in 2007.[1] In addition, over the last decades most river basins in Spain have installed automatic data acquisition systems for hydrological and water-quality monitoring. These systems provide operational knowledge of precipitation, river and channel flow, reservoir volume, and other important water quantity and quality parameters.

The Jucar basin agency (Confederacion Hidrografica del Jucar, CHJ) manages a basin with an area of 42,989 km^2, including areas within several adjacent basins, and which flows to the Mediterranean Sea in eastern Spain (Fig. 13.1). As described in this chapter, the use of models and Decision Support Systems (DSS) has played an important role in the development of the CHJ Basin Plans for almost two decades, as well as in the development and implementation of the SDPs. The SDPs have been formulated according to a proactive approach to drought preparedness and mitigation. They include long-term (planning), medium-term (alert) and short-term (emergency and mitigation) measures that are activated using Standardized Operative Drought Monitoring Indicators (SODMI) obtained from particular combinations of data on precipitation, reservoir storage, groundwater levels, and river flows. The SODMIs and threshold curves for assessment of the drought situation have been calibrated by intensive use of DSS for drought-risk

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[1] Basin plans and Special Drought Plans can be found at the Web pages of the Spanish basin authorities, which in turn can be reached trough the Web page of the Ministry of Agriculture, Food, and Environment: www.magrama.es

Table 13.1 Water abstraction, renewable water resources, and water scarcity index for Spanish basin administrations (Figures in MCM)

Basin authority	Water abstraction	Renewable water resources	Water scarcity index (WA/RWR)
Galicia costa	819	12,250	0.07
Norte	1,692	31,907	0.05
Duero	3,860	13,660	0.28
Tajo	4,065	10,883	0.37
Guadiana I	2,312	4,414	0.52
Guadiana II	219	1,061	0.21
Guadalquivir	3,760	8,601	0.44
Sur	1.350	2,351	0.57
Segura	1.834	803	2.28
Júcar	2.962	3,432	0.86
Ebro	10,378	17,967	0.58
C.I. Cataluña	1,357	2,787	0.49
Baleares	288	661	0.44
Canarias	427	409	1.04

Elaborated by the authors with data from MMA, 2000

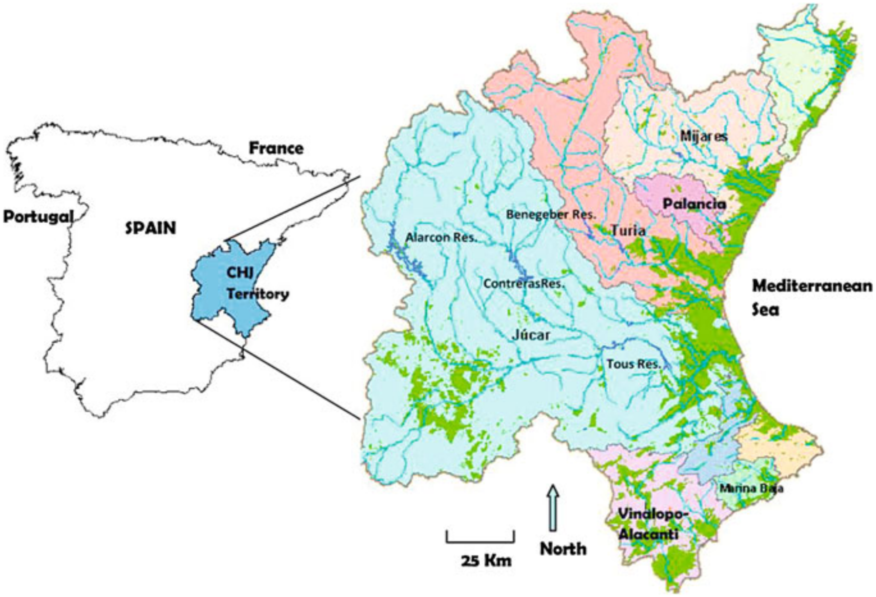

Fig. 13.1 Location of the basins that constitute the CHJ territory

estimation. In addition to their use in the development of the threshold curves used with SODMI, DSSs are also regularly used in real-time management at board meetings to assess drought risks and vulnerability over short- and medium-term time horizons, from a few months to an entire campaign, or even two campaigns.

Between 2005 and 2008, a severe drought occurred in the CHJ area, mainly centered in the two larger basins, Jucar and Turia. This drought is considered the most severe drought in hydrologic terms among the basin's recorded history of hydrological flows, which began in 1940. The objective of this chapter is to describe how the drought was managed, and how the DSS played an important role as a tool that provided information for risk estimation, assessment of effectiveness of mitigation measures, and as a common shared vision of the water resources system in the resolution of conflicts among stakeholders.

13.2 The Jucar and Turia River Basins

Among the several basins included in CHJ territory, the two largest are the Jucar River basin (22,378 km^2) and its neighboring Turia River basin (6,913 km^2). In the Valencia coastal plain, where both rivers terminate, there is a shallow lake called Albufera (2,300 ha), with an associated wetland (23,000 ha), which is situated between the two river mouths. Both, the lake and the wetland, depend on return flows from irrigation areas within both basins, and also on groundwater flows from the coastal aquifer of Plana de Valencia beneath the plain.[2]

The main reservoirs for water supply are Alarcón (1,112 hm^3), Contreras (444 hm^3), and Tous (378 hm^3) in the Jucar basin, and Benageber (221 hm^3) and Loriguilla (50 hm^3) in the Turia basin.[3] Average annual inflows to reservoirs are 1,300 hm^3 in the Jucar basin, and 285 hm^3 in the Turia basin. Groundwater plays an important role in both basins. Both have large calcareous aquifers in the northwestern upper parts, where the rivers emanate, which provide base flows. They also have important aquifers in the middle part, such as the Mancha Oriental aquifer in the Jucar basin, which also used to provide important base flow to the river. Nowadays, it is being overexploited, which is causing the inversion of flows resulting in the river loosing water to the aquifer during spring and summer, which makes the river much more vulnerable with respect to environmental flows.

Water in both basins is used mainly for urban water supply (including industry supply), irrigation, and hydropower generation. The main urban demands are the metropolitan area of Valencia (31 hm^3/year from Turia river, and 93 hm^3/year from Jucar river); the city of Albacete (15 hm^3/year from Jucar river); and the city of Sagunto (8 hm^3/year from Jucar river). Surface water has been used for centuries in the traditional irrigated areas, mainly in the lower Jucar (45,000 ha, using 628 hm^3/year), and the middle and lower Turia (15,000 ha, using 210 hm^3/year), and more recently (20th century) in the middle basin irrigated areas of the Jucar

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[2] A great deal of information about the CHJ and its basins can be found in CHJ 2005, and is available at CHJ website (www.chj.es). Therefore, only the relevant information needed for understanding the chapter will be presented herein.

[3] 1 hm^3 (a cubic hectometer) = 1 MCM (one million of cubic meters) = 1 Gl (one gigaliter) = 10^9 l.

(18,000 ha, using 70 hm^3/year) and the Turia (18,000 ha, using 90 hm^3/year). The two last zones mentioned can use groundwater as a supplement in the case of insufficient surface water deliveries. Another irrigated area in the middle Jucar basin, currently around 90,000 ha, is using around 390 hm^3/year of groundwater from Mancha Oriental aquifer. At present, it can use up to 35 hm^3/year of surface water in order to reduce the aquifer overexploitation.

13.3 Use of the DSS in Planning Phase

During the design of the Basin Plan for Jucar and Turia basins, intensively used DSSs were set up using Aquatool (Andreu et al. 1996), a generalized tool, or DSS Shell (DSSS) produced by Instituto de Ingenieria del Agua y Medio Ambiente de la Universitat Politecnica de Valencia (IIAMA-UPV) to develop DSSs for integrated water resources planning and management. It includes, among other components, modules for basin management simulation, basin management optimization, aquifer flow modeling, drought risk assessment, economic assessment, water quality simulation, and ecological flows analysis. Aquatool has a user-friendly graphical design and database management capabilities, and provides control of the execution of models and on the analysis and reporting of results. The DSSS allows the user to input and modify, in a geo-referenced graphical manner, the configuration of a water resources system. DSSS also facilitates the input and management of graphically geo-referenced data bases containing the physical characteristics of the components of the schemes (e.g., dimensions, hydraulic parameters). Its knowledge bases contain data related to decision variables and management parameters, in order to replicate the judgment of experts in the basin management teams (e.g., priorities, operating rules, indicators for anticipated drought actions). In Fig. 13.2, the schematics of the Turia and Jucar Basins in the DSSs can be seen.

Once the system is completely defined, the user can perform simulations of alternative management schemes under a variety of model assumptions relating to time horizons, climate scenarios, hydrologic processes, and operating rules. Results include flows in the system, state of the elements (e.g., volumes in reservoirs, state of aquifers), and multi-objective performance indicators (e.g., for reliability, resiliency and vulnerability of demands and environmental requirements). Therefore, the model is useful for evaluating design and management alternatives, analyzing planning decisions, and assessing tradeoffs between alternatives. Risks associated to planning decisions also can be assessed since, besides of deterministic analysis, implicit stochastic analysis can be performed. For this purpose, multiple future hydrological scenarios are generated, and probabilities for the variables of interest, as well as probability distribution functions, are obtained from multiple simulations. In the same fashion, risk associated with real-time management of the system can be assessed. In this case, the module for generating future scenarios produces hydrologic scenarios conditioned to the hydrologic state

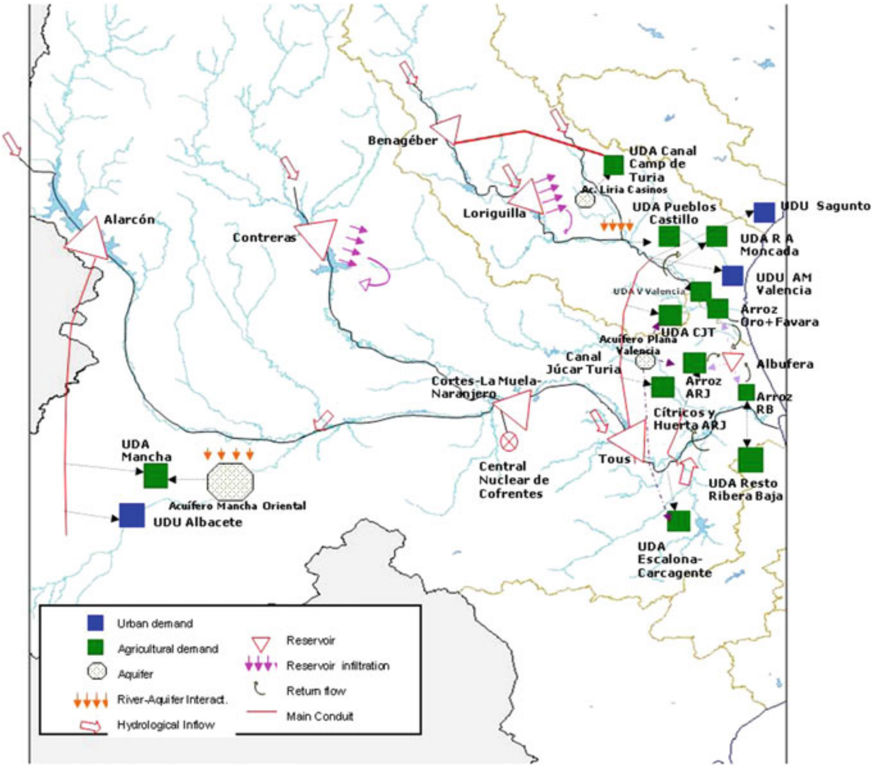

Fig. 13.2 Scheme of the Jucar and Turia rivers system used in the DSS

of the system at the moment of the consultation (i.e., conditioned to recent flows and aquifers state). The results of the analysis can be obtained in the form of written reports (either detailed for the entire time horizon or summarized as mean values and performance indicators), time series and average graphics, probability distribution along a time horizon (i.e., percentiles graphics), or exceedance probabilities for a given variable at a given time. A more detailed description of the DSS tool, as well as of practical applications for integrated planning and management in other Spanish basins, can be found in Andreu et al. (1996).

13.4 Use of the DSS in Drought Planning, Monitoring, and Risk Estimation

As mentioned, since the year 2000, Spanish water law requires that basin agencies develop Special Drought Plans (SDP) in order to turn the traditional reactive crisis management approach into a proactive one. The SDP for CHJ territory (CHJ 2007) includes monitoring for early drought detection, drought stages definition, and the measures to be applied in each of the drought stages. CHJ has developed Standardized Operative Drought Monitoring Indicators (SODMI), which are fully described in the SDP, and also in Estrela et al. (2006). In essence, the SODMI uses real-time information provided by the Automatic Data Acquisition System of CHJ on the state of reservoirs, aquifers, rivers, and precipitation to produce standardized indexes for some selected elements in the basin. These indexes then are combined into a single standardized index for each basin.

The usefulness of the SODMI is derived largely from the simulation results from the DSS. The water resources system management is simulated for a large historical hydrological scenario, with current facilities and demand scenarios, and the different situations of water supply (i.e., normality, pre-alert, alert, and emergency) are correlated with the values of the SODMI, obtaining a calibration of the indexes that renders them useful for early warning, risk perception, and for activating different types of preparation and mitigation measures, according to the situation. Nowadays, drought monitoring is performed on a regular monthly basis, and the reports are displayed in the CHJ website (www.chj.es).

SODMI have provided useful information for early warning and action against drought, as well as for risk perception by the public. Yet, in order to manage droughts, a more elaborate and detailed information system is needed to better assess the risk and the effectiveness of the measures that can be used to modify the risks, and to mitigate the effects of the drought on both the established uses and on the environment. This is why, in addition to the use of the SODMI to monitor the operative drought, CHJ has gone one step further by (1) integrating long-term planning and short-term management and operation into its procedures, thereby providing consistency between those two time scales; and (2) demonstrating that DSS can be very useful for the real-time management of basins, especially during drought episodes and their associated conflict situations. As mentioned above, the Aquatool DSSS allows for the development and use of real-time management models able to assess, for instance, the risk of drought and the efficacy of proactive and reactive measures (Capilla et al. 1998). Indeed, it is being applied on regular basis for the management of the Jucar basin.

In order to decide real-time water allocation, each basin has a Water Allocation Committee (WAC) that meets every month. Depending on the particular situation, the committee decides how much water will be delivered from each source, and how much water will remain in reservoirs. These are participatory committees in which users are represented and information for the decision is provided by technicians of CHJ, including the results of the risk-assessment models. Following the methodology of drought risk and assessment depicted in Andreu and Solera (2006), the probability distributions for all variables of interest are obtained (e.g., deficits in water demands, volumes in reservoir storage, deficits in ecological flows) for every month over the assumed time horizon (e.g., 12, 24, or 36 months). The DSS can show these results in tabular or graphical form, highlighting the evolution of probabilities and percentiles for water demand and for reservoir storage. Cumulative distribution functions of any state or quality variable at any time can be obtained. Then, the WAC analyzes the results and evaluates the situation. If the estimated risks are acceptably low, then there is no need to undertake measures. However, if the estimated risks are seen as unacceptably high, then some measures must be applied. In that case, alternatives with sets of measures are formulated, and the modification of risks and the efficiency of measures are assessed. This iterative procedure can be continued until, eventually, an acceptable value of risk is reached and the process ends. The approach can be applied directly to any complex water resources system, thanks to the models and data management modules included in Aquatool. In fact, it is also implemented in other Spanish basin authorities, such as Tajo and Segura. Without the development of the DSSs, it would be very difficult, if not impossible, to estimate risks with such a complete vision of the consequences of decisions, either concerning management or infrastructure (in this case we refer to infrastructures that can be built in some months within the drought episode, as mentioned below).

13.5 The 2005–2008 Drought Management Experience

During the hydrological year 2004/05, a severe drought started within the Jucar basin. In fact, it has been one of the more intense hydrological droughts registered in the basin in the recorded history (since 1940). This particular hydrologic year from 2004 to 2005 was ranked third, in terms of lowest total inflows to the ensemble of Alarcon, Contreras, and Tous reservoirs; 2005/06 was ranked the lowest.

As Fig. 13.3 shows, in February 2005, a stochastic analysis gave an early warning signal, based on the probabilities of more than 50 % that the hydrological year would end with low storage (between 195 and 390 hm^3 in total, i.e., 10–20 % of reservoirs capacity). In response, water savings in agricultural uses was encouraged, old "drought wells" in the Plana de Valencia Coastal aquifer were

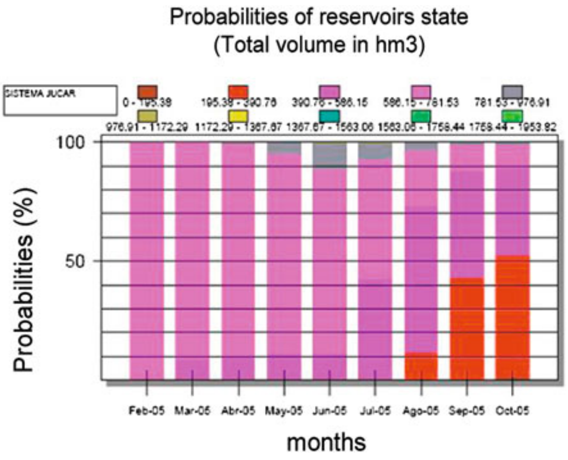

Fig. 13.3 February 2005 assessment of storage probabilities for 2005 campaign

recovered, and new drought wells were identified and drilled. Besides reducing application rates, agricultural use of surface water was reduced further by engaging in conjunctive use with groundwater. For example, the middle basin irrigation area served by the Jucar-Turia canal increased its groundwater extraction which subsequently reduced its surface water consumption by 30 %. Moreover, the operating rules devised for the Jucar River system state that, when the total storage in the ensemble of the three reservoirs fall under an established rule curve, conjunctive use practices must be implemented in the lower basin. Hence, in August 2005, the traditional irrigated areas of the lower basin started to use the drought wells in order to reduce their surface water consumption. It is interesting to note that energy consumption in these wells is not paid by the traditional users, but by the junior rights users and by urban users, who benefit from the surface water in exchange.

At the end of the 2004/05 hydrological year, the hydrological situation did not improve, and a so called "Permanent Drought Committee" (PDC), with special powers to administer the basins of CHJ under emergency situations was set up. The PDC was composed of representatives of CHJ; regional governments (Castilla la Mancha, Valencia, Aragon and Catalonia regions); agricultural, industrial, and urban uses; the Ministry of Agriculture; the Spanish Geological Institute; non-governmental environmental organizations; and labor unions. Hence, it was a participatory committee in which most stakeholders were represented. Its missions were: (1) to take decisions on water management during the drought in order to mitigate the impacts of the drought reaching an equilibrium between the interests of different sectors, of different groups of users in the same sector, and of the environment; (2) to perform a continuous monitoring in order to control the efficacy of the decisions, to follow the evolution of the drought, and its impacts on users, on water quality, and on the environment (water quality in the lower Jucar River and in the Albufera wetland were critical issues, as well as low flows in the middle Jucar River and low inflows to the Albufera wetland); and (3) to authorize emergency works in order to improve control and efficiency of water use, connectivity, additional sources development (e.g., drought wells, direct treated wastewater reuse), and hence, to increase the reliability of the supply.

In March 2006, the SODMI provided the image shown in Fig. 13.4 (left), suggesting a maximum emergency situation in the Jucar basin. The deterministic and stochastic forecasts for the evolution of reservoir storage obtained with the DSS were as depicted in Fig. 13.5. As the figure shows, if no additional measures with respect to the ones taken in the previous year were undertaken, then total storage in the three main reservoirs of the Jucar basin would reach values below 55 hm^3 (minimum environmentally and technically admissible value), and that the probability of ending the campaign above 193 hm^3 was less than 5 %. So, surface water allocated to irrigation was reduced to 43 % of normal supply to traditional users, and to 30 % of normal supply to junior water rights. Supplementary supplies from groundwater of about 40 hm^3 were mobilized, as well as 62 hm^3 from recirculation of water in the rice fields in the wetland area (under a very strict water quality control to avoid salinity build up over tolerable limits).

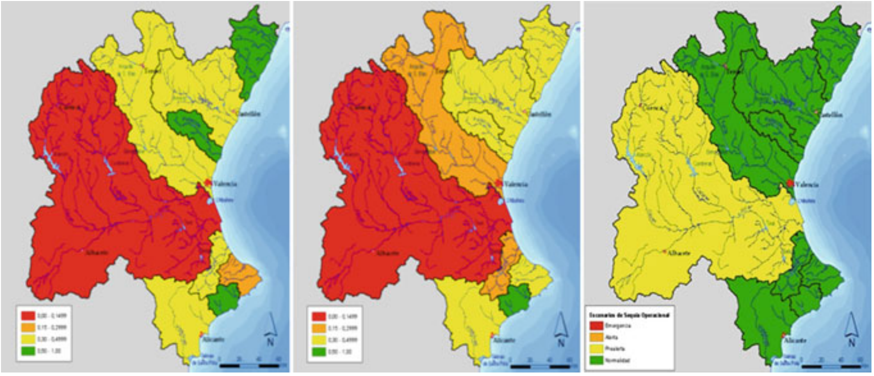

Fig. 13.4 CHJ-operative drought indicators for CHJ basins in March 2006 (*left*), January 2007 (*center*), and March 2009 (*right*). *Green*, *yellow*, *orange*, and *red* colors stand for normal, pre-alert, alert and emergency situations, respectively

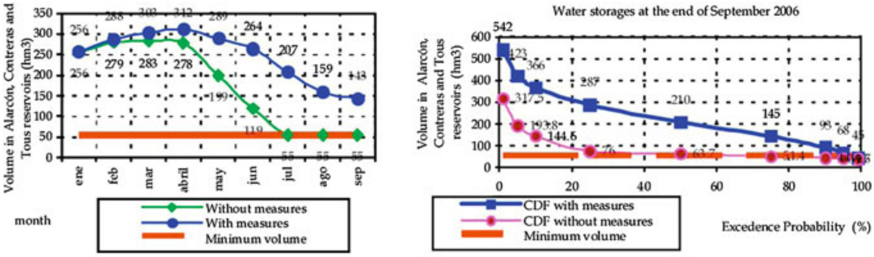

Fig. 13.5 Deterministic (*left*) and probabilistic (*right*) forecasts for the reservoir storage evolution in 2006 campaign

Another measure was to increase the amount of water supplied to the metropolitan area of Valencia from the Turia basin up to 49 hm^3/year, hence reducing the supply from the Jucar River. In order to achieve this without harming the reserves in the Turia basin, it was agreed that approximately 36 hm^3 of adequately treated waste water should be directly supplied to traditional agricultural users in the lower Turia basin as a partial substitute for surface water. Furthermore, CHJ temporarily purchased 50 hm^3 of water rights from agricultural users of the Mancha Oriental aquifer to avoid extracting this groundwater, which resulted in lower abstraction from the middle Jucar River and an improvement in environmental flows. The decision to adopt these measures was based on the results of the DSS. Figure 13.5 presents the deterministic and stochastic forecasts for the evolution of reservoir storage, as calculated in April 2006, from the application of these measures. It can be seen in the figure that final storage was very much improved (i.e., from 55 to 143 hm^3 in the deterministic forecast, and a 50 % of probabilities of ending with more than 210 hm^3), and the plan, including the measures, was approved and implemented.

Additional measures included increase of efficiency in water use (a main pipeline and two distribution pipelines that were under construction were speeded up and adapted as a substitute for the old main canal and ditches for traditional farmers in the lower Jucar); improvement in control devices for surface water diversion, further enlargement of the drought wells system, anticipated conjunctive use of surface and groundwater, and increasing the direct reuse of treated wastewater). Also included in the measures adopted were special monitoring programs for the environmental protection of critical spots, with a focus on the middle reach of the Jucar River where groundwater abstraction in Mancha Oriental aquifer can cause river depletion up to the point of drying up the river bed; the lower reach of the Jucar River, where low flows and high pollution loads from urban waste water can cause severe problems; and the Albufera lagoon, which depends on irrigation returns for its inflows (additional inflows were provided by 26 hm^3 of treated waste water with nutrient removal and green filtering). Water quality improvement measures (e.g., removal of algae, and artificial aeration) were applied in the lower Jucar River. Although not a specific measure of the drought management, a waste water treatment plant that was under construction was put in service and reduced considerably the above-mentioned pollution loads. Finally, a special groundwater monitoring program was also included among the measures in order to control the volume of water extracted, water levels, and the quality of the water.

In hydrological year 2006/2007 and 2007/2008, total hydrological inflows were higher than in the year 2005/2006 in the Jucar River, but still under the average, and the distribution was irregular. As a result, the reservoirs in the upper part of the basin received less water, aggravating the low-flow problem in the middle Jucar River. Hence, the plans for 2007 and 2008 campaigns approved by the PDC adopted very similar measures to those included in the 2006 campaign, but with greater intensity in order to achieve the same degree of drought mitigation and environmental protection as in 2006/2007. In the Turia basin, the situation passed from pre-alert in March 2006 to alert in January 2007, due to low hydrological inflows (Fig. 13.4). On 30 September 2008, as a consequence of the continued measures and of a slightly better hydrology, the total reservoir storage in Jucar Basin was 260 hm^3—the best end to a campaign since 2004. In the hydrological year 2008/2009, furthermore, abundant rainfall brought the basins near normality, as shown in Fig. 13.4 for SODMI for March 2009. Normality was attained in the Jucar basin by March 2010, after a very wet winter.

13.6 Conclusions

DSS Shells (DSSS) (i.e., generalized tools to build DSS) bring the possibility of relatively easy, systematic and homogeneous application of DSS over wide regions, and also provide guidance in the development of the DSS. An example of the practical use of one of such DSSS (Aquatool) that has been used in practice for many years was presented in this chapter. In Integrated River Basin Management, the integration of long-term planning and short-term management and operation is very important to provide consistency between those two time scales. DSS can be very useful for the real-time management of basins, particularly during drought episodes and their associated conflict situations. Aquatool DSSS allows for the development and use of real-time management models that are able to assess, for instance, the risk of drought, and the efficacy of proactive and reactive measures. It is being applied on regular basis for the management of basins in the Jucar basin, in Spain.

As a result, the worst drought in modern times in the Jucar basin, lasting from 2005 to 2008, passed with relatively low economic and environmental damages; urban supply was always fulfilled; and conflicts among users were solved in an atmosphere of transparency and cooperation promoted by participatory approaches. This last point was also fostered by the methodologies used for the analysis, which relied very much on the results of DSS, and their role as tools for the assessment of risk and of the efficiency of mitigation measures. In fact, the DSS provided a common shared vision of the water resource system by the different groups of stakeholders.

Some of the measures to deal with the drought were implemented for the first time in Jucar basin, and included water rights purchases; voluntary cuttings in groundwater extraction from Mancha Oriental Aquifer; direct treated wastewater reuse by traditional irrigation in lower Turia basin; conjunctive use of surface and groundwater by traditional irrigation in the lower Jucar Basin, with energy expenses been paid by users with junior rights; and improved control measures for control of water use and environmental flows. These measures proved to be very effective in the mitigation of the drought impacts. Therefore, many of these measures adopted in the campaign plans and approved by the Permanent Drought Committee will become permanent practices. Convenient remodeling of the measures to adapt for ordinary management, and the lessons learned from this experience will help in the production of new versions of the Basin Plan, and of the Special Drought Plan of Jucar basin.

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Chapter 14
Drought as a Catalyst for Change: A Case Study of the Steenkoppies Dolomitic Aquifer

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Abstract Karst aquifers in dolomites are the single most important type of aquifer in South Africa. One such aquifer is the Steenkoppies Aquifer, situated west of Tarlton (26°02′–26°13′ S, 27°29′–27°39′ E), which covers an area of 213 km^2 with a catchment area of 311 km^2. A perennial spring, Maloney's Eye that discharges into the Magalies River, serves as the only natural outlet for the groundwater stored in the aquifer. Discharge from this spring, for the last 100 years, varied between 0.05 and 1.035 $m^3\ s^{-1}$ with an average of 0.455 $m^3\ s^{-1}$. The standardised precipitation index (SPI) was used to evaluate the potential affect of meteorological and hydrological drought on this aquifer. The region has experienced two distinct periods of severe and extreme meteorological drought during the last 27 years (1990–1992 and 2002–2005). The cumulative rainfall departure (CRD) method was used to evaluate the relationship between precipitation and spring discharge. There is a reasonable correlation between the CRD, with a short-term moving average of 9 months and a long-term moving average of 60 months, and

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the discharge from Maloney's Eye. However, since 1987, the actual discharge from Maloneye's Eye is lower than the simulated discharge, indicating that external factors such as abstraction may play a role and enhance hydrological droughts. These droughts have provided the primary stimulus for a change in the behavior and attitude of the groundwater users relying on the Steenkoppies Aquifer, which resulted in processes being initiated to measure, monitor, and manage water abstraction from the Steenkoppies Aquifer.

14.1 Introduction

South Africa is characterized by different climate types and regimes with precipitation being both highly seasonal and unevenly distributed (Fauchereau et al. 2003). South Africa is also viewed as a semi-arid country with a mean annual potential evapotranspiration (ET_o) of 1,800 mm a^{-1} and a mean annual precipitation of 475 mm a^{-1}, 385 mm a^{-1} less than the world average of 860 mm a^{-1} (Conga 2006). Precipitation varies from 800 mm a^{-1} in the east, to less than 200 mm a^{-1} in the west, with approximately 65 % of the country receiving less than 500 mm a^{-1} (Meyer 2007).

Arable and permanent crops cover about 15.7×10^6 ha, of which 1.5–1.6 million ha are irrigated (Hoffman et al. 1990; Backeberg et al. 1996). This accounts for 59 % (7.8×10^9 m^3 a^{-1}) of the total water requirements that support 25–30 % of the national agricultural production (Backeberg 2005). Agriculture contributes 4.2–5.3 % of the gross domestic product (GDP), but if backward and forward linkages to manufacturing and marketing sectors are taken into account, the total impact on the economy increases to more than 30 % (Backeberg 2005). On the other hand, drought can reduce the GDP growth on average by 0.5–1.2 % per year (Finance Week 2003).

As surface water becomes more limited, groundwater sources are increasingly exploited, especially in rural and arid areas. South Africa has a variety of aquifer types, ranging from crystalline basement to Karoo dolerite of which karst aquifers, especially in dolomites, are the single most important type of aquifer (Hubert et al. 2006). Exploitation of groundwater occurs mainly in the Western Cape and eastern and northeastern parts of South Africa (DEAT 2009). It is estimated that 236×10^9 m^3 of groundwater is stored in South African aquifers with an average groundwater exploitation potential (AGEP) of 19×10^9 m^3 a^{-1} in average years and 16×10^9 m^3 a^{-1} during a drought (Woodford et al. 2006; DWAF 2006). Approximately 6 % of the AGEP is currently abstracted, of which 64 % is used for irrigation (Woodford et al. 2006).

The aim of this chapter is to provide an overview of a South African groundwater scheme, based on the Steenkoppies Aquifer, to show that excessive abstraction of an aquifer enhances hydrological drought, that these droughts can provide the primary stimulus for change in the behavior and attitude of the groundwater users, and to highlight that these changes resulted in processes being initiated to measure, monitor, and manage water abstraction from the Steenkoppies Aquifer.

14.2 Case Study: Steenkoppies Dolomitic Aquifer

14.2.1 Description of Study Area

The Steenkoppies Aquifer is situated in the central interior of South Africa, west of Tarlton (26°02′–26°13′ S, 27°29′–27°39′ E) (Fig. 14.1). It covers an area of 213 km^2 with a catchment area of 311 km^2 (Holland 2009). Precipitation occurs mostly during summer (October–March) as thunderstorms with a mean annual precipitation of 668 mm (Table 14.1).

The topography consists of undulating plains that vary between 1,550 m above sea level in the east and rise towards the north and west to a height of 1,640 m (Hobbs 1980). There is an absence of significant surface water drainage (Fig. 14.1), and it is currently believed that a perennial spring, Maloney's Eye,

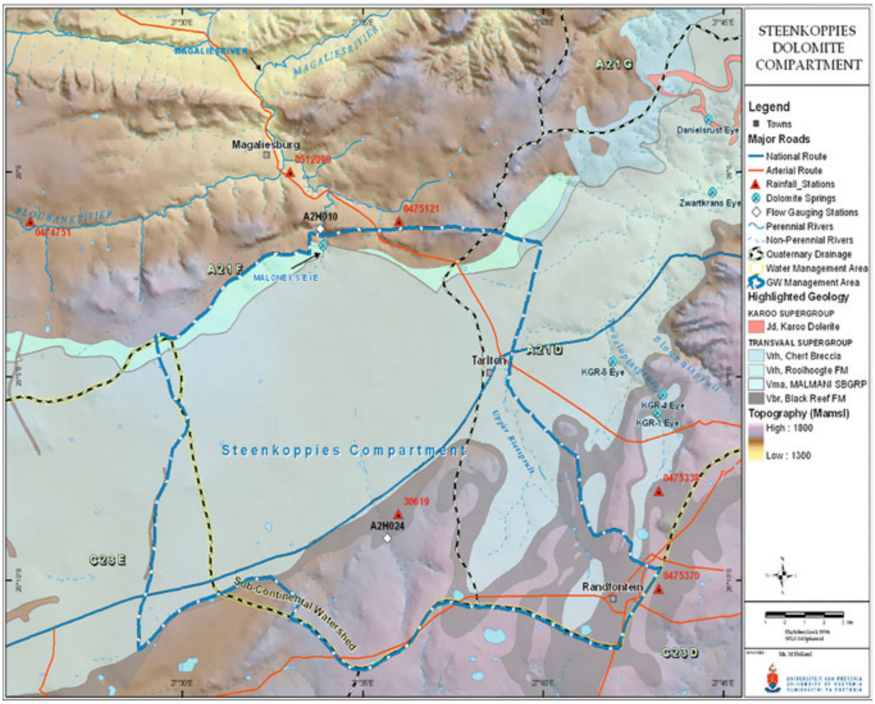

Fig. 14.1 Steenkoppies Aquifer

Table 14.1 MAP characteristics for the Steenkoppies Aquifer

Year (record)	MAP	Years above or below long term MAP		Years MAP > 1,000 mm	Years MAP < 550 mm	MAP (mm)	
		Below	Above			Min	Max
1908–2008	668	55	45	3	24	348	1081

situated approximately 750 m north of the northern boundary of the aquifer at a height of 1,490 m serves as the only significant natural outlet for the groundwater stored in the aquifer (Hobbs 1980). The discharge from this spring varied over a period of 100 years, between 0.05 $m^3 s^{-1}$ (lowest in March 2007) to 1.035 $m^3 s^{-1}$ (highest in February 1979), with an average of 0.455 $m^3 s^{-1}$. It flows into the Magalies River to the north of Maloney's Eye (Fig. 14.1), that feeds the Hartbeespoort Dam, currently a highly polluted impoundment (Oberholster and Ashton 2008).

A conceptual model for the Steenkoppies Aquifer is presented in Fig. 14.2. The aquifer is bounded in the east by the Tarlton West Dyke and in the west by the Eigendom Dyke, both striking north–south. The area is underlain by dolomitic limestone, which, together with interbedded chert lenses form the Malmani Subgroup of the Chuniespoort Group, dipping to the northwest at 5–20° (Bredenkamp et al. 1986). The outcropping quartzites of the underlying Black Reef Quartzite Formation, form the southern boundary of the compartment, while to the north an unconformity separates the Chuniespoort Group from overlying quartzite and shale of the Pretoria Group, effectively forming the northern boundary of the compartment (Foster 1984). Maloney's Eye is situated above the groundwater level of the dolomite drainage area, at the intersection of the Maloney's Eye dyke and the east–west striking fault zone within the shales/quartzites of the Rooihoogte/Timeball Hill Formations (Pretoria Group). Therefore, the existence of the Eye could be attributed to a dyke of low permeability and the cross-cutting of the fault zone representing the main water conduit from the dolomite into the shales and quartzites (Fig. 14.2) (Holland 2009).

The main agricultural activity is cultivation under irrigation, and water for households, and irrigation is abstracted from the Steenkoppies Aquifer. Abstraction from more than 200 boreholes and a network of pipelines, developed and maintained by each water user, supply the water for irrigation. Irrigation systems consist primarily of center pivots and quick coupling pipes to a lesser degree, with drip and micro emitters restricted to crops grown under plastic and shade-cloth covered structures. No restrictions on drilling, size of boreholes and pumps or compulsory measuring of water abstraction or monitoring of groundwater levels are currently enforced. However, a limited number of flow meters were installed recently as part of a pilot study initiated by famers on the aquifer. The water is of exceptional quality with a maximum total dissolved salt (TDS) concentration of 240 mg l^{-1} (Kuhn 1988). The possibility of using the aquifer as a water supply source for the city of Rustenburg and as part of an emergency groundwater

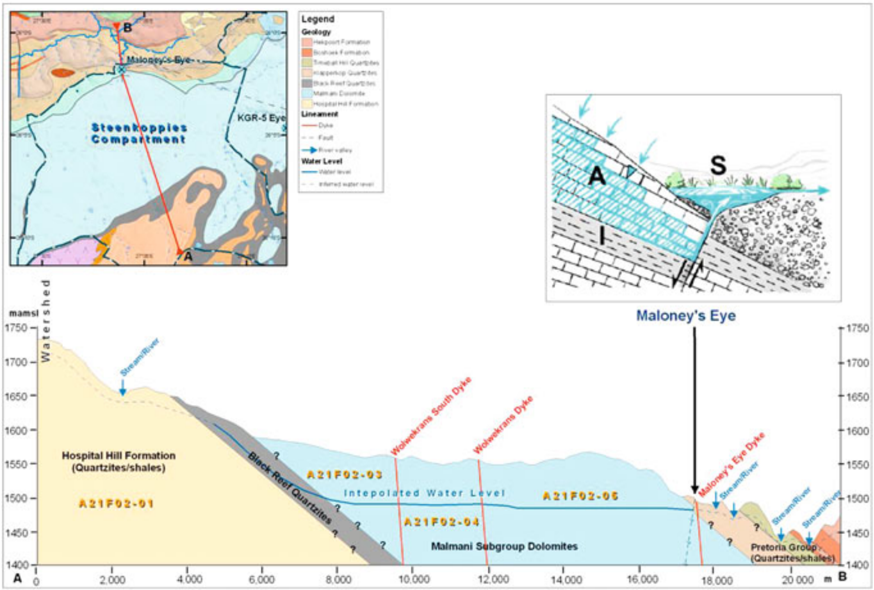

Fig. 14.2 Conceptual model for the discharge at Maloney's Eye

pumping scheme was investigated by the Department of Water Affairs in the mid-1980s. However, the capital investment and running cost made the project unviable at that time (Bredenkamp et al. 1986; Kuhn 1988).

14.2.2 Socioeconomics

Data on the socioeconomics of irrigated agriculture, based on the Steenkoppies Aquifer, was collected by means of a semi-structured personal interview (Stevens et al. 2005) with each farmer in 2007/08. A summary of the data is presented in Table 14.2. Highly productive soils, high-quality irrigation water and close proximity to major cities and airports render the Steenkoppies Aquifer ideal for intensive irrigated agriculture. The largest producers of carrots in Africa, and mushrooms and chrysanthemums in South Africa, are all drawing on the Steenkoppies Aquifer. The area is characterized by intensive farming with vegetables and flowers as the main crops grown on approximately 3,640 ha (Table 14.2). Work is provided to more than 4,000 people with more than US$900,000 paid in monthly salaries, which contributes greatly to the local economy. Capital investments are in the order of US$100 million, with an annual turnover of approximately US$66 million (Table 14.2). Social programs such as accredited skills development and HIV awareness programs have been implemented, and on-site medical clinics with full-

Table 14.2 Socioeconomic data for the Steenkoppies Aquifer

Type of crops grown	Vegetables, maize, wheat and flowers
Total ha under irrigation	3,640
Groundwater abstraction from WARMS registration data base	27.4×10^6 m^3 a^{-1}
Groundwater abstraction from preliminary validation	22.4×10^6 m^3 a^{-1}
Permanent workers	2,945
Temporary workers	1,072
Managers	177
Living on farm	1,475
Monthly salaries	US\$900,000[a]
Turnover	US\$66,000,000[a]
Capital investment	US\$102,000,000[a]

[a] Exchange rate assumed 7.6 ZAR per USD

time nurses and crèche facilities are also supported and funded by growers dependent on the aquifer.

Until recently, farmers on the Steenkoppies Aquifer responded well to their social responsibility, but did not fully comprehend and adequately manage their most important natural resource, namely, groundwater. Being irrigation farmers, they depend on the sustainability of the groundwater resource and, until as recently as 2008, no management structure, monitoring of groundwater levels, measuring of abstraction or scientifically based irrigation scheduling took place. However, the pressure of possible further legal action against groundwater users has forced the farmers to establish the Steenkoppies Aquifer Management Association (SAMA) in 2008, to facilitate the institutionalization of a Water Users Association as required by the National Water Act (NWA 1998).

14.2.3 Historic Overview of Water Usage

In 1980, agriculture consisted mainly of maize, with vegetable farming limited to the southeastern and cattle farming to the northwestern part of the aquifer. The area was also characterized by numerous small holdings in which farming was restricted to maize, small-scale vegetable production and a few head of cattle (Hobbs 1980). The calculated volume of groundwater abstracted from the aquifer for irrigation in 1980 was 4×10^6 a^{-1}, which represented 36 % of the lowest annual discharge from Maloney's Eye, measured up to 1980 (Hobbs 1980). In 1996, cultivation under irrigation increased to 1,952 ha and groundwater abstraction to 20.1×10^6 m^3 a^{-1} with vegetable production covering more than half the irrigated area (Barnard 1997). Currently, 269 properties with a total area of 11,077 hectares have water rights for an estimated 3,786 ha. Groundwater abstracted for irrigation is between 27.4×10^6 m^3 a^{-1} (registered WARMS users

[Water Use Authorization and Registration Management System]) and 22.4×10^6 m^3 a^{-1} (preliminary validation volume) with vegetables and flowers as the main crops (Table 14.2).

14.2.4 Precipitation and Discharge from Maloney's Eye

A single representative precipitation time series, similar to the period of discharge records for Maloney's Eye, was compiled from four meteorological stations (Fig. 14.3) (Holland 2009). These four stations showed a similar mean annual precipitation (MAP), where the maximum deviation of MAP between stations was below 10 %. The time series was compiled by calculating a weighted average (using a squared inverse distance weighting method) of all monthly precipitation records available for a given time period. However, between 1983 and 1985 and from 1990 onwards, data was used from only one meteorological station situated on the aquifer. Data collected from this station (Fig. 14.4) indicates that the mean monthly potential evapotranspiration (ET_o) is greater than the mean monthly precipitation for every month. Therefore, during an average rainfall year a water deficit for crop production will exist, that needs to be supplemented with irrigation.

In Table 14.1, a simple analysis of the MAP (Fig. 14.3) is given. The mean annual precipitation is 668 mm, with 55 years below and 45 years above the mean. The minimum annual precipitation over the period was 348 mm and the

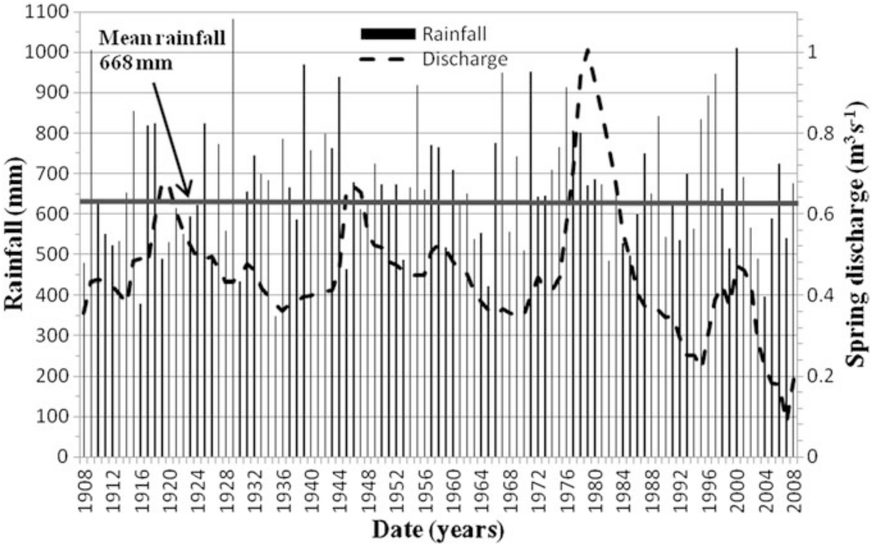

Fig. 14.3 Mean annual precipitation (*MAP*) on the Steenkoppies Aquifer and spring discharge at Maloney's Eye

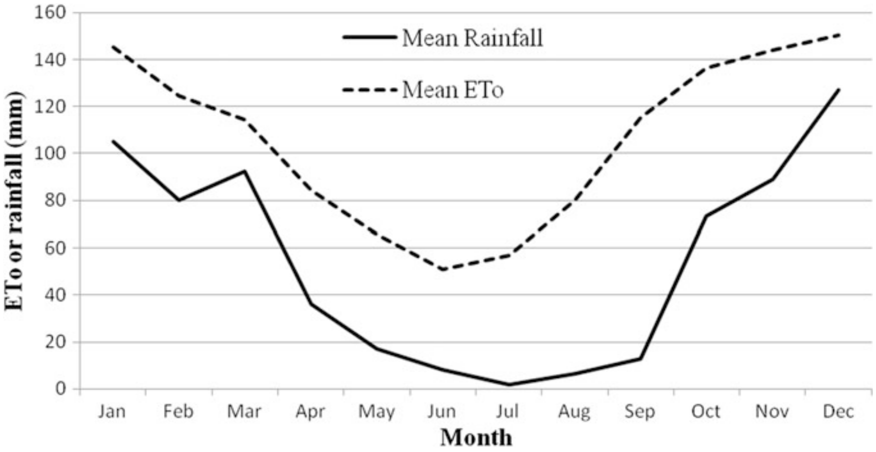

Fig. 14.4 Long-term monthly mean precipitation and evapotranspiration on the Steenkoppies Aquifer

Table 14.3 SPI values classification

SPI values	Class
≥2.00	Extremely wet
1.50–1.99	Very wet
1.0–1.49	Moderately wet
−0.99–0.99	Near normal
−1.00 to −1.49	Moderate drought
−1.50 to −1.99	Severe drought
≤–2.00	Extreme drought

maximum 1,081 mm. A MAP of 550 mm was arbitrarily taken as a reference for particularly dry years, and 24 years fell into this category.

Drought is a complex physical and social phenomenon with widespread significance. It does not usually occur country-wide, but rather is often limited to specific regions. The most commonly used drought definitions are grouped into four categories: meteorological, agricultural, hydrological, and socio-economic (American Meteorological Society 1977). All droughts originate from a lack of precipitation and, therefore, drought can be viewed as a shortage of precipitation over a usually prolonged period of time, with the impact on society depending on its intensity and duration (Rouault and Richard 2003). Different types of droughts can have different time-scales. For example, a typical time-scale for agricultural droughts can be three to six months (typical growing period for most crops) or even less when a crop is at a critical growth stage, when lack of precipitation results in crop damage. Meteorological drought, when atmospheric conditions result in the absence or reduction in precipitation, can develop quickly and end abruptly over a very short period of time (Heim 2002). Hydrological drought, on

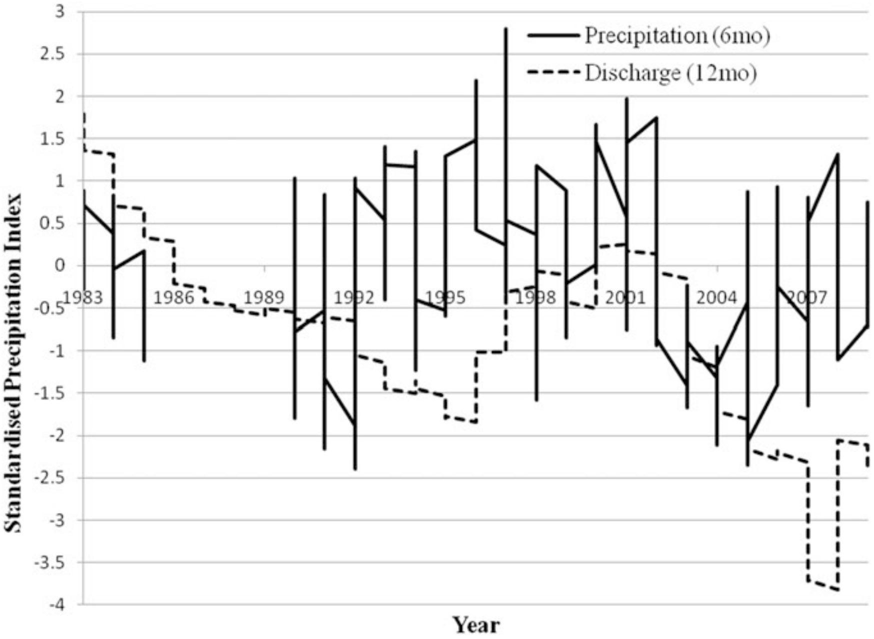

Fig. 14.5 SPI computed for time scales of six months for precipitation and 12 months for spring discharge at Maloney's Eye

the other hand, is associated with the scarcity of cumulative precipitation over a longer time-scale (one to two years or more) and it affects surface and groundwater supply (Meigh et al. 1999; Fiorillo and Guadagno 2009). It takes longer for a reduction in precipitation to become evident in groundwater levels and, therefore, it is possible that a hydrological drought can be out of phase with meteorological droughts (Rouault and Richard 2003). Abstraction may also enhance naturally occurring hydrological droughts through over-exploitation of groundwater (van Lanen and Peters 2000).

The standardized precipitation index (SPI) (McKee et al. 1993) is a useful and widely accepted index to evaluate meteorological droughts (Guttman 1999; Fiorillo and Guadagno 2009; Nalbantis and Tsakiris 2009). Using the SPI as the indicator, a functional and quantitative definition of drought can be established and a classification system for drought can be developed accordingly (Table 14.3) (Guttman 1999). The SPI was calculated for precipitation data (six-month time scale) from the only weather station on the aquifer and for the discharge from Maloney's Eye (12-month time scale). These results are presented in Fig. 14.5. Data from the weather station is available from 1983 until the present time, except for a three-year period (1986–1989) when the weather station was out of commission.

From Fig. 14.5, two distinct periods of meteorological drought, 1990–1992 and 2003–2005 (1990 and 2002 classified as severe and 1991, 1992, 2004 and 2005 as extreme drought), can be distinguished. Consecutive years of meteorological drought in 1990–1992 resulted in a severe hydrological drought in 1995–1996 (Fig. 14.5). A period (1993–2002) of near-normal and extremely wet conditions (except 1994 and 1998) resulted in an increase in discharge from Maloney's Eye. Figure 14.5 also indicates that cumulative years of extremely wet conditions are needed (1996 and 1997) to substantially increase the discharge from Maloney's Eye. Consecutive years of meteorological drought in 2003–2005 resulted in an extreme hydrological drought from 2005 to 2009 (Fig. 14.5). However, it is clear from these data that an abnormal decrease in discharge from Maloney's Eye occurred during this latter period that cannot be explained by climatic conditions only.

The drought in 2004 was more severe (annual precipitation was 59 % of MAP) and wide spread, with six provinces in South Africa declared disaster zones and as many as four million South Africans at risk of food shortages (Anonymous 2008). However, during the period 1990–1994, four of the five years had precipitation below the mean, and during 2000–2004 a steady decline in precipitation occurred with precipitation below the mean for the period 2002–2005 (and for 2007) indicating that deficiency in precipitation occurred over a prolonged period of time (Figs. 14.3 and 14.5). Coinciding with these periods of lower precipitation, reductions in discharge of 0.346–0.18 m^3 s^{-1} (1990–1995) and 0.446–0.113 m^3 s^{-1} (2002–2006) from Maloney's Eye are evident with a more drastic decrease in discharge for the latter period (Figs. 14.3, 14.5 and 14.6). This drastic decrease in discharge, reaching its lowest value in 2007, can be attributed to the cumulative decrease in precipitation, severity of the drought in 2004, the delayed effect between meteorological and hydrological drought and excessive abstraction of groundwater that enhances hydrological drought (Figs. 14.3, 14.5 and 14.6).

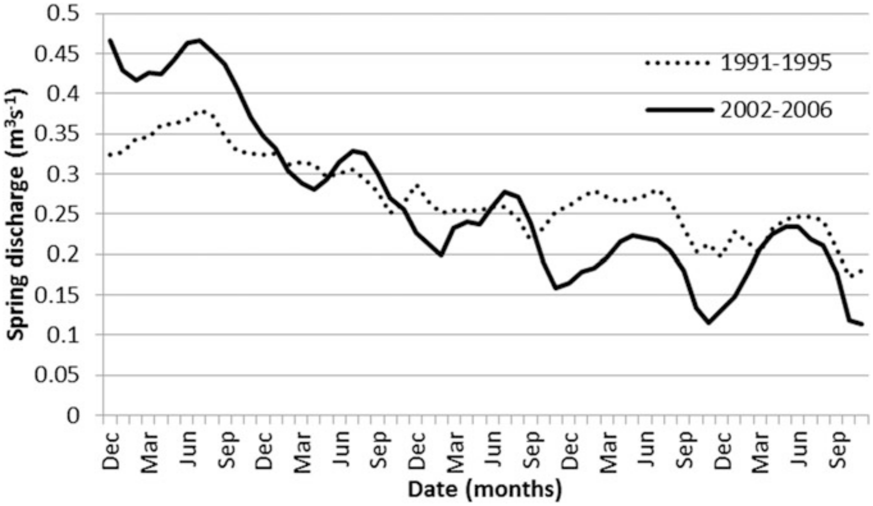

Fig. 14.6 Decrease in spring discharge at Maloney's Eye for the period 1990–1995 and 2002–2006

14.2.5 Response of Downstream Water Users

In 1995, a petition from farmers downstream of Maloney's Eye (surface water users from Magalies River) was sent to the Minister of Water Affairs and Forestry, demanding that the catchment area (Steenkoppies Aquifer) of Maloney's Eye be declared a groundwater management area and that the withdrawal of groundwater must cease (Barnard 1997). Consequently, the minister considered issuing a moratorium on the abstraction of groundwater (from the Steenkoppies Aquifer) and surface water (from the Magalies River) for irrigation use. Above-average precipitation for 1995–1997 (Fig. 14.3) brought some relief, and the demands were not pursued further.

In 2004, the following chain of events emerged:

- During the first half of the summer of 2004, shallow boreholes on the Steenkoppies Aquifer used for household purposes dried up.
- In December 2004, directives were issued to farmers on the Steenkoppies Compartment to stop irrigation using so-called "illegal pivots." After consulting with the Department of Water Affairs and Forestry (DWAF), farmers were allowed to continue with their farming practices if they engaged in a validation process to determine their existing lawful water use.
- In March 2007, the Magalies River Crisis Committee initiated a lawsuit against DWAF for not protecting the ecology of the Magalies River. This lawsuit demanded that water abstraction from the aquifer be reduced, with the percentage reduction depending on the discharge from Maloney's Eye. Irrigation was also confined to restrictive time schedules.
- Groundwater users on the Steenkoppies Aquifer opposed the lawsuit. Farmers were allowed to proceed with irrigation with the understanding that they must establish a water user association according to the National Water Act (NWA 1998).

14.2.6 Discharge and Cumulative Rainfall Departure Method

The relationship between precipitation and spring discharge was evaluated with the cumulative rainfall departure (CRD) method. The CRD method is based on the premise that equilibrium conditions develop in an aquifer over time and that the average rate of loss relates to the average rate of recharge of the system (Xu and van Tonder 2001). The natural groundwater level fluctuation is related to that of the departure of rainfall from the mean rainfall of the preceding period. If the departure is positive, the water level will rise and vice versa (Bredenkamp et al.1995). Therefore, the CRD method can be used to determine if an external factor, e.g. abstraction, influences the equilibrium conditions.

The CRD method is represented mathematically as:

$$a_v^1 CRD_i = \sum_{n=1}^{i} Rn - k\sum_{n=1}^{i} R_{av} \quad (\mathrm{i} = 0, 1, 2, 3\ldots\mathrm{N})$$

Where Rn is monthly precipitation with subscript “i” indicating the i-th month and “av” the average. The exploitation factor k is defined as $k = 1 + (Q_p + Q_{out})/(A.R_{av})$, with Q_p the abstraction, Q_{out} the discharge, A the area and R_{av} the mean rainfall. If $k > 1$ then abstraction and/or natural discharge take place, if $k = 1$ then no abstraction occurs (Xu and van Tonder 2001). The equation was adjusted to consider the long-term groundwater fluctuations and short-term delay from precipitation to groundwater recharge.

Generally the CRD-graph mimics the spring discharge reasonably well with a short-term moving average of nine months and a long-term moving average of 60 months, except for the extremely high discharge obtained during the period 1976–1985 (Fig. 14.7). Since 1987, however, a clear discrepancy exists between expected discharge and precipitation, with actual discharge lower than the simulated discharge (Fig. 14.7). This discrepancy can be explained by excessive abstraction from the aquifer, especially during the drought periods 1990–1994 and 2002–2005 and 2007, when farmers relied heavily on groundwater for growing their crops.

A cumulative plot of precipitation versus spring discharge reveals the distinct increase in spring discharges for the period 1976–1985 (Fig. 14.8). This can be attributed to a 10-year (1971–1981) period of above-average precipitation (Fig. 14.3), indicating a cumulative effect on discharge. This occurrence can be

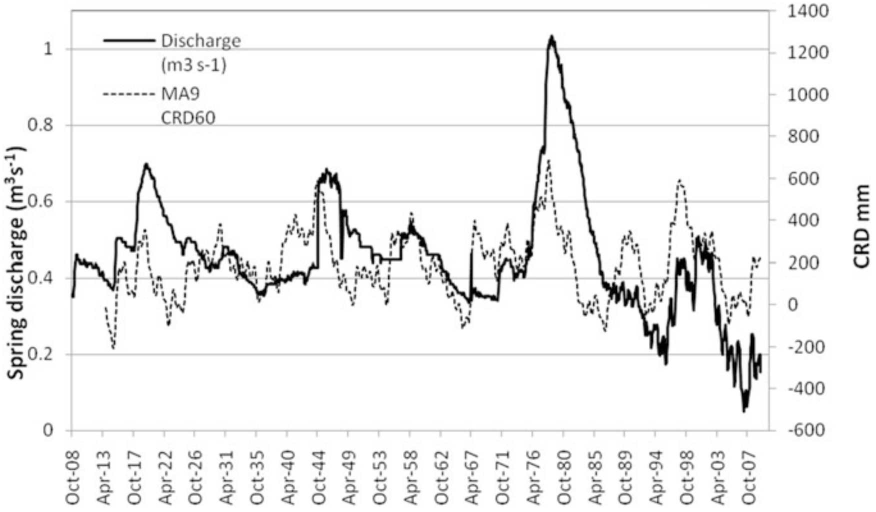

Fig. 14.7 Spring discharge at Maloney’s Eye compared with simulated discharge determined with the CRD method (MA9—short-term moving average of nine months and CRD60—long-term moving average of 60 months)

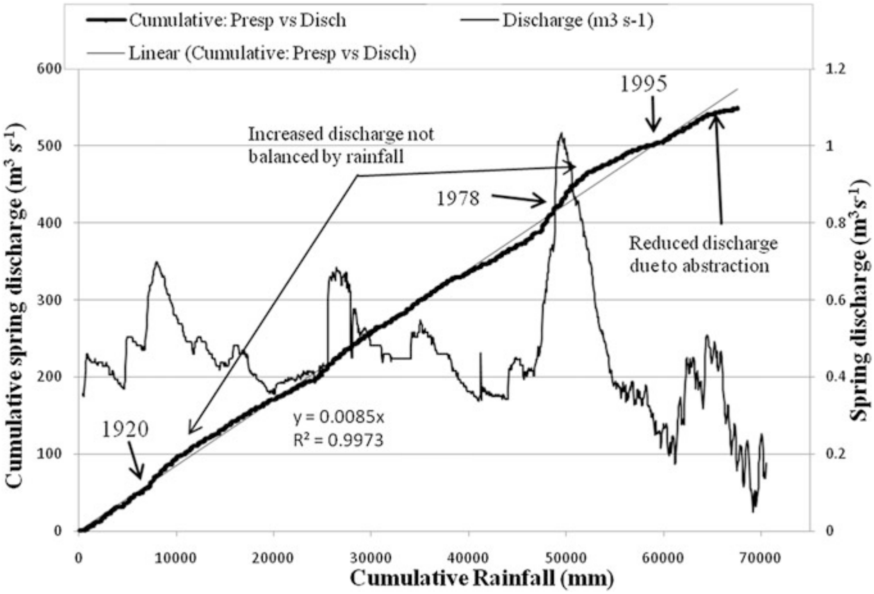

Fig. 14.8 Cumulative spring discharge at Maloney's Eye versus cumulative rainfall

explained by the duality of the recharge process in karst aquifers, in which an early immediate response is possible due to intake via fissures and fractures (conduit type karst), and a late delayed phase which consists of water percolating slowly through soil and rock of lower permeability (diffuse karst type) and greater thickness, also known as the "Epikarst" zone (Fiorillo and Guadagno 2009).

A direct relationship between spring discharge and groundwater levels also exists (Fig. 14.9). The lowest groundwater levels recorded in the area correspond closely to the lowest spring flow recorded in March 2007 (0.05 m^3 s^{-1}). The mean groundwater level in this area ranges from 1,488 to 1,491 m above mean sea level (m.a.m.s.l.) and confirms the flat hydraulic gradient of this system, which are attributed to high transmissivities and low topographic gradients. The sensitivity of the groundwater level to the discharge at Maloney's Eye is evident, with the groundwater table depths fluctuating only between 2.3 and 5.5 m over the last 24 years.

14.2.7 Change in Perception and Behavior

The exploitation of a shared groundwater system is a typical problem of common property, since the resource is limited and not that visual. If the goal of individual water users (private) is to maximize profit, a private solution to manage the groundwater system is inefficient due to the following reasons (Roseta-Palma 2003):

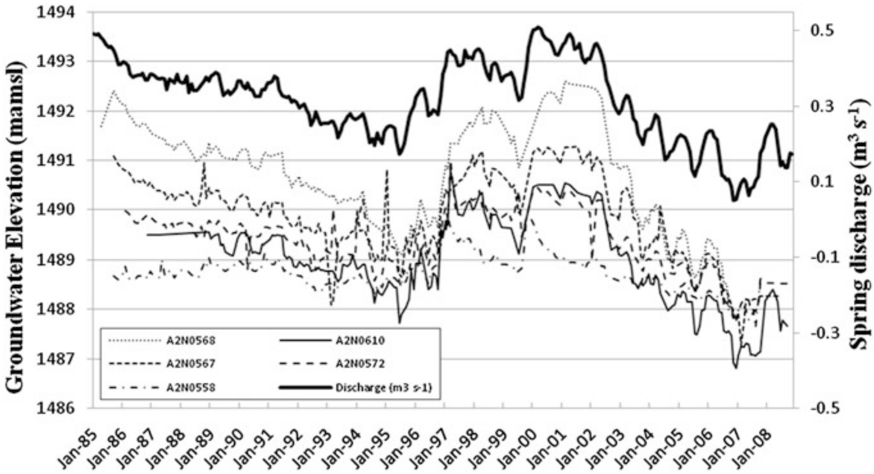

Fig. 14.9 Spring discharge at Maloney's Eye versus groundwater elevation for six different boreholes

- Because groundwater supply is limited, each unit extracted by a specific water user is no longer available to other users, and the only way to lay claim to a unit of groundwater is to pump it. There is, therefore, no incentive to save water, since other water users have the same access to the groundwater.
- Pumping costs depend on groundwater depth, and extraction costs will increase with the lowering of the groundwater level. Individual water users do not consider the detrimental effect of their pumping on other water users, so again there is little incentive to save water.
- If an aquifer is susceptible to contamination resulting from the users' actions, then additional externalities can occur. For example, groundwater polluted by one user can impose external costs on all other groundwater users.

The effectiveness of an aquifer management strategy is dependent on the geohydrological properties, storage coefficient and transmissivity and on community participation for sharing water (Kulkarni et al. 2004). However, changing the perception and attitude from private interest to include public interest (water users from a broader community), including the interest of down-stream water users, takes time and economic and human resources. This is because new agricultural innovations (technical, ideas, processes) are adopted primarily due to their impact on individual yields and profitability (Zilberman et al. 1997). The final decision to adopt or reject an innovation is consistent with the farmers' (actors') self interest; and the rate of adoption and final level of adoption is fundamentally linked to the actual benefits of the adoption by individual actors (Abadi Ghadim and Pannell 1999). However, economic considerations, and direct and indirect costs of innovations often determine the success or failure of the adoption of the innovation, especially when costs exceed an actor's ability to pay (Wejnert 2002).

In the case of the Steenkoppies Aquifer, droughts prompted down-stream farmers to act and exert pressure on up-stream groundwater users and government agencies (DWAF) that mobilized funds and resources to actively pursue a solution for the enhanced hydrological drought due to excessive abstraction on the Steenkoppies Aquifer.

The following changes occurred:

- Groundwater users initiated and partly financed the process for the establishment of a water users association.
- A constitution for the water users association was developed through an intensive public participation process that included surface water users.
- Some groundwater users moved their winter production away from the Steenkoppies Aquifer.
- A pilot study was launched to develop a protocol for the installation of, and data collection from flow meters, to monitor water abstraction from the aquifer.
- Groundwater users are increasingly implementing scientific-based irrigation scheduling methods.
- More efficient pipelines and irrigation equipment are being installed.
- DWAF facilitated the process of establishing a water users association.
- A comprehensive study was financed by DWAF to characterize the hydrogeology of the aquifer and thereby help improve understanding of how the groundwater system works.

The above points highlight the importance of the region and the need to further improve management of the groundwater systems. Key research needs to address this are listed in the next section.

14.3 Future Research Needs

The National Water Act (NWA 1998) makes provision for a reserve. The reserve consists of two parts, the basic human needs reserve and the ecological reserve (NWA 1998). In the case of the Steenkoppies Aquifer, this means that a minimum discharge from Maloney's Eye must be maintained for the essential needs of individuals, such as water for drinking, for food preparation, for personal hygiene, and to maintain the ecology of the downstream river system. Calculation of the reserve needs to take into consideration both the current and future needs. There are several areas that need to be researched to improve management of the Steenkoppies Aquifer to ensure adequate environmental flows through both wet and dry periods. These include:

- The possibility to guarantee the reserve by abstracting water from a sub compartment within the aquifer and pump it to Maloneye's Eye during periods with low discharge must be investigated.

- An accurate water balance for the Steenkoppies Aquifer needs to be developed before compulsory licensing of water use can take place and to provide a basis for a groundwater management plan.
- Hydrological droughts tend to lag meteorological droughts and, therefore, abstraction can enhance and be responsible for the severity of hydrological droughts. A model that relates meteorological data to groundwater recharge must be developed to help improve management of the groundwater system.
- If competition between stakeholders for access to a water resource exists, the priority to use water needs to be determined through negotiation. In the case of the Steenkoppies Aquifer, the priority for water use between the environment, groundwater users, and surface water users needs to be determined and implemented.
- The possibility to use water pricing and water trading to encourage the allocation of water to either redress inequities or for higher value uses must be investigated.

14.4 Conclusions

An increase and intensification of agriculture over the last 30 years on the Steenkoppies Aquifer have resulted in an increase in groundwater abstraction for irrigation. Two distinct periods of severe and extreme meteorological drought (1990–1992 and 2002–2005) were experienced during the last 27 years. These periods of meteorological drought were followed by severe and extreme hydrological droughts (1994–1996 and 2005–2009). Discharge from Maloney's Eye reached its lowest value in 2007, due to the cumulative decrease in precipitation, severity of the drought in 2004, the delayed effect between meteorological and hydrological drought, and the excessive abstraction of groundwater. There is also a reasonable correlation between the cumulative rainfall departure (CRD) and Maloney's Eye discharge. However, since 1987 the actual discharge from Maloneye's Eye has been lower than the simulated discharge based on the CRD method, indicating that external factors, such as abstraction, have enhanced the severity of the hydrological droughts. Results of this study have clearly demonstrated that drought provided the primary stimulus for change in the attitude and behavior of groundwater users, which have resulted in processes being put in place to measure, monitor, and manage water abstraction from the Steenkoppies Aquifer.

Acknowledgments This work was supported in part by the Water Research Commission (through the project Standards and Guidelines for Improved Efficiency of Irrigation Water Use from Dam Wall Release to Root Zone Application; project nr. K5/1482/4), Department of Water Affairs, University of Pretoria, the Cooperative Research Centre for Irrigation Futures, and CSIRO.

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Chapter 15
Evaluation of Groundwater Flow System Functioning in Mexico to Reduce Drought Impacts

J. J. Carrillo-Rivera and S. Ouysse

Abstract Approximately 97 % of continental water on Earth is groundwater; the remainder includes surface water, water in the atmosphere, and water in living organisms. For Mexico to cope with drought conditions and minimize environmental impacts of human water usage, water source dynamics must be understood and utilized in the most efficient way. Groundwater moves from its recharge to its discharge area in flow systems, traveling through paths of different length and depth, resulting in flows that can be both local and regional. Regional flows are currently supplying about 95 % of the required water in arid regions, such as in Mexico's San Luis Potosí Basin, which is the focal point of this study. The main objective is to highlight the importance of understanding groundwater flow systems to better identify the sources of recharge for any particular aquifer. Aquifer recharge can be derived from both local and regional sources and thus groundwater policy must consider the spatial and temporal dimensions of recharge in an attempt to efficiently manage extractions. Indeed, only through a better understanding of the biophysical relationship among groundwater components and drought can informed decisions be made.

15.1 Introduction

Mexico has a long history of precipitation insufficiency, resulting from climatic situations that have lasted for periods of months and years. These shortages of rainfall have negatively affected the water supply of towns and rural communities

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as well as their agricultural activities. Such conditions have existed for decades in the northern arid- and semi-arid regions of Mexico where lack of rainfall has been more severe in some years than in others. Local settlers in those regions have adjusted by appropriating surface water through gravity transfer. However, groundwater has become a central element to agricultural and economic activities in the region. Currently, groundwater is the main water source, supplying up to 95 % of the domestic and industrial needs—including some 70 % for irrigation—in the northern arid- and semi-arid regions of Mexico.

The first inhabitants of the arid- and semi-arid regions in Mexico used groundwater from springs as their main water supply as in the desert area of Cuatro Ciénegas in the State of Coahuila, whose springs withstand long drought conditions (see Chap. 10). Drought conditions were mitigated by extracting water from springs that originated from intermediate or regional flows. Later, shallow wells were built to compensate for inadequate spring water to cope with the constantly increasing water needs and recurring drought (Gutiérrez de MacGregor et al. 1997). Afterwards, in 1847, construction of boreholes began in Mexico to supplement water needs when surface water and hand-dug wells were inadequate to meet aggregate water need. The first boreholes were artesian, which implied that water was obtained by natural pressure; unfortunately, the rapid proliferation of boreholes reduced the pressure and access to this water (Domínguez and Carrillo-Rivera 2007). The decrease in water-level elevation was initially solved with the introduction of a turbine pump. However, the unregulated groundwater systems essentially are common property and, thus, boreholes again proliferated.

During this period of rapid groundwater extraction, there was little hydrogeological information identifying regional and underground hydraulic connectivity among watersheds (which were considered as aquifers). From a technical perspective, the original focus of interest in early hydrogeological studies (that formally began in the second half of the 1960s) was the hydraulic response of aquifers. Aquifers store and permit groundwater transfer from the recharge to the discharge area, making groundwater available to boreholes for extraction. Yet any particular aquifer may have hydrologic connections with other aquifers, a characteristic often overlooked in earlier studies that incorrectly defined an aquifer as a surface drainage basin. This lack of adequate information about groundwater generated misleading expectations for a long-term supply of high-quality water. Additionally, while technological advances in borehole drilling and the turbine pump made groundwater easy to reach, its extraction affected the natural yield of springs in terms of quantity and quality, and indiscriminate groundwater extraction led to severe environmental impacts on the physical and biological conditions, and on related ecosystems (Carrillo-Rivera et al. 2008).

Recently, there has been an increased recognition of linkages of groundwater systems within and across basins through the use of Flow System Theory (FST). FST recognizes the importance of both groundwater and its underground flowing characteristics from a different path and depth along which each flow system is displaced in the vertical dimension, due to contrasting physical and chemical conditions. Spatially, this theory suggests that groundwater sources in arid- and semi-arid regions are dependent upon temperate regions in which precipitation is abundant and prevailing high topography and lithology (fractured rocks) of the terrain suggest the presence of recharge areas for regional flow systems to develop. Once water has infiltrated into the ground, though, it might take several millennia to reach natural discharge areas and extraction sites in arid- and semi-arid regions.

Climate variability, as well as climate change, will heighten the vulnerability of regions and communities to natural changes of hydrological phenomena. Based on an expected global mean annual precipitation decrease, it is predicted that future climate conditions could lead to the presence of drought (or its increase) in many regions of the American continent (http://www.epa.gov/climate/climatechange/science/futurepsc.html), together with most of the Mediterranean, northern Africa, and northern Sahara, among other regions. It is also theorized that such an effect will be coupled with an environmental temperature increase. Exacerbating the consequences of these changes is the expected increase in population and productive activities in arid- and semi-arid regions that will produce additional pressure on existing groundwater flow systems. It has been argued that even without climate change, most developing countries will be confronted with serious water problems by the middle of the twenty-first century, due mainly to an insufficient understanding of the functioning of their groundwater sources.

In the following sections, it is provided a more detailed description of Flow Systems Theory and how to go about identifying whether an aquifer is dependent upon both local and regional recharge. A case study using the San Luis Potosí basin in northern Mexico will be used to illustrate the major points. It will be concluded with a summary emphasizing that effort to efficiently manage an aquifer through, perhaps, permits, subsidies, or charges will require policy makers to better understand the spatial and temporal dimensions of aquifer recharge.

15.2 Groundwater Flow Systems, Drought, and Climate Change

Flow system characterization is a valuable tool in defining groundwater vulnerability to climate change at local or global scales. This knowledge may assist in defining an appropriate strategy to sustain and protect local flows from drought conditions, and to take advantage of regional and intermediate flows that have the lowest response to climate change and drought effects, but are subjected to trans-boundary groundwater issues. Therefore, defining the hierarchy of prevailing groundwater flows and their relation to neighboring basins is of paramount importance, as recharge of extracted water may not necessarily infiltrate in the basin under drought conditions.

Generally, groundwater is constantly moving from its recharge area to its discharge area (i.e., lake, river, wetland, spring). Groundwater moves in what modern literature refers to as Gravitational Groundwater Flow Systems (Tóth 1995, 2008), referred hereafter as Flow Systems for simplification. Each system travels through specific and separate paths with a different circulation length and depth, and often through different geological units (Fig. 15.1). The contrasting traveling characteristics of groundwater produces distinctive physical properties that reveal particular traits, such as depth to water table (shallow in discharge areas, deep in recharge areas); specific flow direction (vertical downward in recharge areas, horizontal in transit areas, and vertical upward in discharge areas); temperature characteristics (cold in recharge areas, warmer in discharge areas); and chemical conditions such as high dissolved oxygen (DO) levels and Redox potential (e,g., which measures oxidation and reduction processes), and low pH and salinity in recharge areas. Low DO, high pH and salinity characterize discharge areas.

A flow that has a short travel distance and recharges and discharges in the same valley is termed local flow. In a local groundwater flow system, water takes from months to years to travel between recharge and discharge areas. These flows usually transfer the best natural quality water, but a reduction in precipitation would evidently diminish recharge and stored water. Thus, the identification of local flows is required to enhance actions to protect them from contamination and from inefficient extraction that might have significant environmental and economic consequences.

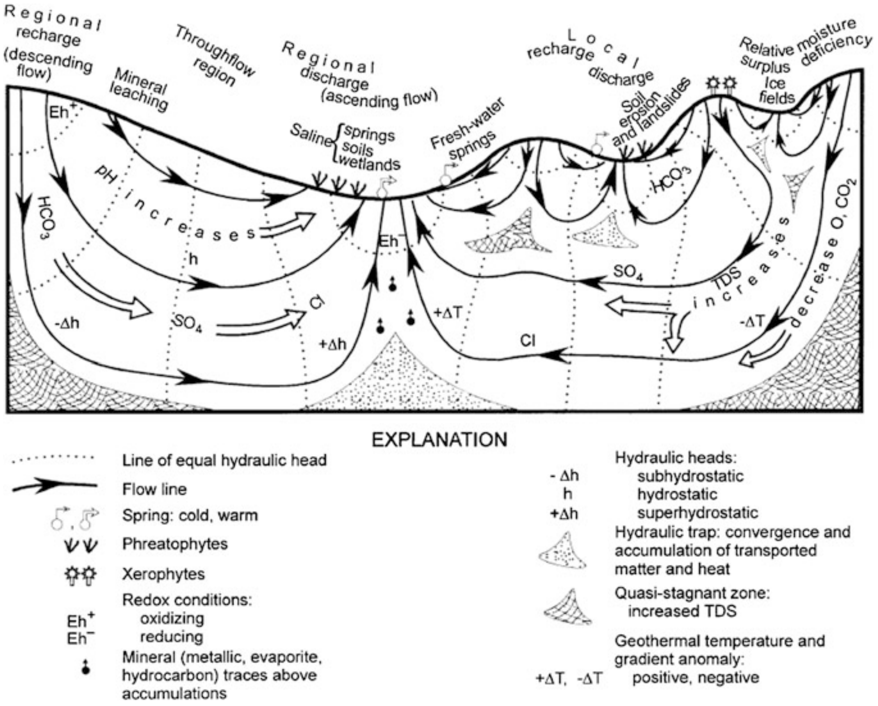

Fig. 15.1 Illustration of local, intermediate and regional flow systems; adapted from Tóth (2008). Note that a regional flow travels from one surface drainage basin to another. The former could be located in a temperate region, and the latter in an arid- or semi-arid region

Alternatively, a flow that initiates its traveling path in a surface drainage basin and discharges in a neighboring basin containing at least one local flow, is termed intermediate flow, and flow generated from the highest elevation that travels to the lowest position in the region is a regional flow in which the discharged water quality is characterized by high temperature, salinity, and pH, as well as low Eh and DO. Intermediate and regional flow systems might travel from one region into another, with their recharge processes usually taking place in an area located far away from the discharge area (natural or by means of boreholes). Indeed, regional flows, according to the geological and climate characteristics of Mexico, travel several hundreds of kilometers, often flowing from a temperate region to arid- and semi-arid regions. Urban growth and related economical development of main cities and important agricultural establishments rely on these types of flow. Unfortunately, urban growth and agriculture usually take place without giving proper consideration to the connectivity between surface water and groundwater, and their availability.

Increasing climate variability may lead to intensification of certain components of the hydrological cycle, which will affect recharge and discharge areas of local flow system leading, in some cases, to drought conditions. In some regions, an increase in magnitude and frequency of extreme events, such as a cyclic sequence in time of drought and flooding, has been observed (Alconada-Magliano 2008). From the historical perspective, these cyclical conditions have been recorded for the Argentinean Pampas (plains) since the seventeenth century. However, such historical data is lacking in Mexico. Knowledge of the spatial and temporal patterns of precipitation, evapotranspiration, and the hydrology within a region, though, is necessary to develop sustainable basin management strategies. Failure to understand flow systems will not only impact economic activities in the agricultural and urban environments, but also ecosystems and the services they provide. Indeed, climate variability may deepen regional weakness of components of the hydrological cycle from region to region, so investigations need to incorporate local climate variation scenarios.

Adaptation to climate variability requires different actions among which the application of science-based knowledge about the integration of groundwater flow systems becomes essential in developing a sustainable strategy for management of groundwater extraction. Such integration should be part of any water administration framework aimed to minimize and control related drought effects that will result in negative environmental impacts predicted for future climatic conditions in several parts of the world, mainly in developing countries. Population increase and productive activities in arid- and semi-arid regions place additional pressure upon existing flow systems. Altering the ecosystems in these regions through unsustainable groundwater extraction, results in increases in soil erosion, land subsidence, extracted water quality changes, landscape deterioration and biodiversity loss, as well as desiccation of rivers, lakes and springs, among others (Carrillo-Rivera et al. 2008).

15.3 A Case Study: the San Luis Potosí Surface Drainage Basin, Mexico

A study held in San Luis Potosí basin (SLP basin) provides evidence of the importance of regional groundwater flow systems to define availability of water during drought conditions and its contribution in the socio-economic development of this basin. At the center of the basin is the city of San Luis Potosí, which is located approximately 400 km north–west of Mexico City at the south–eastern end of the Sierra Madre Occidental mountain range, and is the capital of the state of the same name (Fig. 15.2).

15.3.1 Climatic Characteristics and Geological Framework

The San Luis Potosí basin (SLP basin) is a closed-surface drainage basin; the city is located in the middle of a plain and lacks any perennial runoff. The climate in

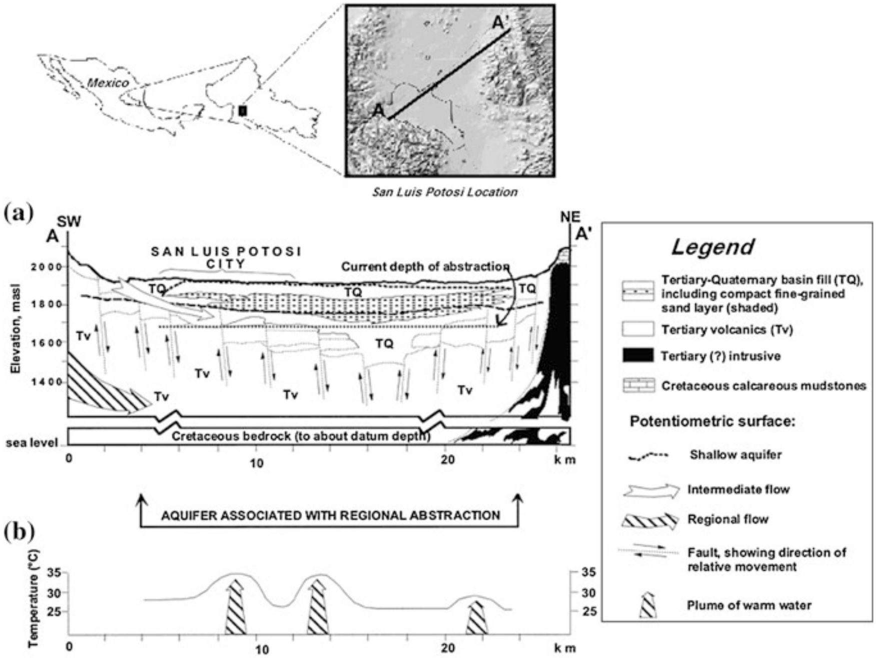

Fig. 15.2 Diagram showing intermediate and regional flows beneath the San Luis Potosí surface drainage basin. The position of Cretaceous bedrock is interpreted from geophysical data. (Adapted from Carrillo-Rivera 2000). The b section shows temperature of groundwater discharged from boreholes tapping the deep aquifer unit along the line of section as for October 1987

the SLP basin is semi-arid, with an average annual precipitation of approximately 400 mm/year, most of which falls during a few days in the summer months (June–September). The mean annual and summer temperatures are 17 °C and 21 °C, respectively. The elevation of the basin floor is between 1,850 and 1,900 m above mean sea level. The average annual potential evaporation is approximately 2,000 mm (1961–1990). Runoff collected in the two existing dams, San José and El Peaje, provides a seasonal water supply of about 0.20 m^3/s for SLP city. Consequently, about 95 % of the total current water consumption (>2.60 m^3/s) is derived from a deep aquifer unit.

The SLP basin is located in a drought-intensive environment. As such, the development of this basin and others in arid and semi-arid regions is constrained; unless additional water sources are found. Given the lack of sufficient surface water sources in many of these regions, groundwater is increasingly considered as a possible solution. Groundwater could be a potential solution to drought if the surface water basin under drought relies on inter-basin groundwater flow to circumvent an insufficient surface water supply; therefore, the functioning of the complete groundwater storage needs to be understood.

General hydrogeological features of the study area are illustrated in Fig. 15.2. The SLP-Basin is within the Sierra Madre Occidental Groundwater Region (Carrillo-Rivera 1988), which is about 1,500 km long and 220 km wide. This mountain range contains acid silica-rich (rhyolitic) rock units of similar nature to those of the SLP basin. The porous nature of the volcano-tectonic grabens and related normal fault system permit groundwater flow to travel within this basin along neighboring (surface) drainage basins. It should be noted that fractured rock zones related to fault systems have higher hydraulic conductivity than the rest of the region through which groundwater finds long flow paths to follow (Carrillo-Rivera 1992).

Using geothermometry, it was possible to establish that regional groundwater flow takes place at an average depth of about 1,700 m, through a Tertiary-Quaternary sequence just above the geological basement. This area included an undifferentiated Cretaceous calcareous mudstone and a post-Cretaceous quartz-monzonite intrusive rock (Carrillo-Rivera et al. 1992). No geothermal activity has been identified within 300 km of this drainage basin, which implies that observed groundwater temperature (>40 °C) is due to the depth at which vertical flow occurs; water of the intermediate flow has a contrasting temperature of about 25.5 °C.

15.3.2 Aquifers' Description

Also illustrated in Fig. 15.2 are two aquifer units within the SLP basin: a minor shallow aquifer unit, and a deep aquifer unit that is only partially penetrated by boreholes. The top of the deep aquifer at the center of the plain is at a depth of approximately 200 m. Boreholes bottom out at 350–450 m in lava flows, tuff, and sediments. In the SLP drainage basin, the deep aquifer unit (granular and fractured material) is confined at the center of the plain by a compact fine-grained sand layer, which mostly consists of quartz and sanidine (90 % by volume) and some carbonates and clays (halloysite, illite, and montmorillonite) (Cardona 2007). The confining layer, which separates the shallow and deep aquifers, is 50–150 m thick, extends some 300 km^2, and has low hydraulic conductivity ($\approx 10^{-9}$ m/s). This layer is found under most of the plain except at its edges. The top of this unit is about 100 m below the lowest part of the plain surface. Leakage from the shallow aquifer to the deep aquifer unit is negligible, as indicated by chemical evidence (Cardona et al. 2008a, b).

Previous studies show two closely adjacent major potentiometric depressions[1] coinciding with the trace of normal faults. Potentiometric contours indicate that there is no natural groundwater outflow occurring from the groundwater balance budget zone. Such potentiometric depressions result from intensive groundwater extraction, which increased from 0.8 m^3/s in 1972 ($\approx$90 deep boreholes) to 2.7 m^3/s in 1987 ($\approx$280 boreholes) and led to an insignificant drawdown rate difference (from 0.90 to 1.35 m/year, respectively) (Carrillo-Rivera 1992). This unexpected small lowering of the potentiometric surface (i.e., water table) is due to the entry of regional flow induced to the extraction level of boreholes by means of vertical ascending flow, a process that can deeply alter the hydrological system response to groundwater extraction.

15.3.3 Flow Systems Identification

In general, the average temperature of groundwater samples taken from SLP basin have increased by as much as 15 °C from the early 1960s to the late 1980s (Carrillo-Rivera et al. 2002). Groundwater with a temperature greater than 30 °C accounts for about 70 % of the total current extraction from boreholes tapping the deep aquifer unit. This high-temperature water in the SLP basin is related to a regional groundwater flow system (Carrillo-Rivera et al. 1992), as defined by Wallick and Tóth (1976), and evidenced by concentrations of boron (0.17 mg/l), fluoride (3.1 mg/l), sodium (53.2 mg/l), and lithium (0.19 mg/l), elements that are present in the rhyolitic environment[2] where water flows through. Observed concentrations of lithium and sodium also imply that this water has had a long residence time.

Some 30 % of extracted water is cold (25.5 ± 1 °C), suggesting an intermediate groundwater flow system as defined by Wallick and Tóth (1976). This water has a shorter residence time than the high-temperature water, as suggested by the levels of boron (0.03 mg/l), fluoride (0.4 mg/l), sodium (14.6 mg/l), and lithium

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[1] An example of previous studies is Carrillo-Rivera (1992). A potentiometric surface represents the level that water will rise to in a screened well; when water is extracted, the surface deflects around the well, creating a cone of depression.

[2] Rhyolitic environments are formed by specific igneous volcanic extrusive rocks.

(0.01 mg/l). Such chemical content is a consequence of the nature of the granular material in the aquifer, and the shorter residence time of the water (Carrillo-Rivera et al. 1992) as compared to water emanating from regional flows.

There is a lack of evidence for the presence of discharge areas within the drainage basin. The nearest spring with high-temperature water (36 °C) is approximately 30 km south of the basin. Local flows, as defined by Wallick and Tóth (1976), occur only during and shortly after rainfall. Such characteristics suggest that the flow systems as related to the SLP basin probably have recharge and discharge areas located outside the basin that need to be properly defined as to establish hydrological related effects along the flow system.

15.3.4 Groundwater Balance and Flow System Response

The standard groundwater-balance equation (change in storage = recharge − extraction + inflow − outflow) was applied to the SLP basin (Carrillo-Rivera 2000). Groundwater-related characteristics coincide with the conceptual hydrogeological model; the computed value for storativity (0.001) for the confined part of the deep aquifer unit was derived numerically from aquifer-test analyses (Carrillo-Rivera 1992). A computation of the total yearly extraction from the deep aquifer was 85×10^6 m^3 (error ± 20 %). Groundwater inflow travelling to the center of the confined extraction zone was calculated at 4.7×10^6 m^3/year (as for October 1986–September 1987) using transmissivity values of 1.9×10^{-4}–1.9×10^{-3} m^2/s and 8.1×10^{-4}–4.0×10^{-3} m^2/s for the fractured media and granular material, respectively. As all water flows towards the balance-zone, outflow is negligible. There is a yearly average horizontal groundwater flow of 4.7×10^6 m^3) moving towards the extraction zone. Due to observed confined conditions (Fig. 15.2), all inflow seems to be coming from horizontal flow.

An important aspect is that the assumption of horizontal flow in the groundwater-balance equation fails to explain the remarkable temperature rise as extraction time has increased. The computed values of the storage coefficient are not reflected in the reported small drawdown difference of 0.9 m/year for 0.8 m^3/s extraction, and 1.35 m/year for 2.7 m^3/s extraction (in 1972 and 1987, respectively). If the computed storage value of 0.001 is applied to the area of balance, water-table (or hydraulic head) response due to current extraction (2.7 m^3/s) would have reached a depth beyond 200 m. These scenarios of extraction and hydraulic head response suggest an additional water component entering from outside the surface drainage basin. Therefore, groundwater from regional flow becomes paramount in the hydrological understanding of the functioning of the SLP basin, from which adequate general water policies and particularly drought-relief schemes may be devised. Consequently, if the functioning of the regional flow system is overlooked, errors derived from the conceptual model to cope with drought conditions may produce severe environmental impacts.

For example, the overlooked vertical component of regional flow within the SLP basin is responsible for the observed changes in water quality (i.e., increase in fluoride and sodium); this flow component needs to be recognized, as it is possible to be controlled (Carrillo-Rivera et al. 2002). Increases in concentrations of these chemicals and other water-quality characteristics may cause serious health problems among children and the elderly and impact crop yields as reported in 2002 by Castellanos et al. (e.g., increases in sodium and pH levels in irrigation water decrease the ability of a plant to take micronutrients such as iron and zinc). Such water quality changes have also been observed in other basins throughout Mexico (e.g., Guanajuato and Aguascalientes).

Finally, it was considered the age of the groundwater in the SLP basin. Obtained isotopic water age using ^{14}C and with ^{13}C corrections (Cardona et al. 2007) derived from 17 studied boreholes taping regional flow suggests that groundwater in the SLP basin entered the system more than 6,000 years ago. Intermediate flow systems have been defined to be between 1,300 and 3,000 years of age. Similar groundwater age estimates have been obtained for other volcanic regions in Mexico (Edmunds et al. 2002) suggesting that regional and intermediate, as well as local groundwater flow systems are widely present. As such, and given the presence and reoccurrence of drought, efficient development for the SLP basin depends on "old" water that comes from regional flows; therefore, it is of paramount importance to consider the groundwater flow system as one unit that needs to be defined not only within the basin but in terms of its recharge and discharge areas located, perhaps, beyond the basin boundaries.

15.4 Concluding Remarks

An analysis of the physical and chemical characteristics of the water in the aquifers within the San Luis Potosí drainage basin suggest that these groundwater flows are dependent upon recharge from both local and regional sources. As such, management that is considering balance between extraction and recharge with additions must understand the spatial dimension over which these activities can occur and still have an impact on the aquifer's water depth and quality. To better understand these spatial relationships, it is here suggested that researchers, water managers, and policy makers to acknowledge the potentially valuable role offered by flow systems theory. This theory helps to highlight the fact that water table levels and quality from an aquifer located in one geographically defined basin may be dependent on additions and extractions from not only flows from within that particular basin, but also from additions and extractions from flows outside the basin, albeit over a different time scale.

While similar conclusions are likely be drawn for other aquifers and basins worldwide, further research on the San Luis Potosí basin is necessary and important, as knowledge of where the flow systems emanate will aid in: (1) supporting policies intended to protect the vulnerable regional system to recharge changes (quality and quantity); (2) verifying if the regional flow is under extraction elsewhere beyond the SLP basin; (3) identifying the location of the recharge area of the SLP basin to propose some protective measures in the basin and along the flow path; (4) controlling the rate of extraction in time and space to minimize the loss of water quality (for example, through the inflow of fluoride-rich water[3] which is a characteristic of groundwater facies in SLP basin as well as along the Sierra Madre Occidental); (5) controlling the present extraction scheme to minimize subsidence effects and control artificial recharge with sewage effluents; and (6) developing programs of payment for hydrological environmental services in the recharge areas of the regional flow. All of these possible objectives or management opportunities can be aided and improved upon with a better understanding of the position of the recharge area of the regional flow systems, which will then allow a groundwater monitoring program to be implemented.

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[3] In high concentrations (>1.5 mg/l), soluble fluoride salts are toxic and interfere in processes like bone and teeth formation.

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Chapter 16
Drought and Climate Change in the Murray-Darling Basin: A Hydrological Perspective

Mac Kirby, Francis Chiew, Mohammed Mainuddin, Bill Young, Geoff Podger and Andy Close

Abstract The Murray-Darling Basin experiences frequent droughts and, at the time of this writing, parts of it are in the grip of the worst drought in the 110 years of comparatively high-quality records. In this chapter, we consider the term drought to be several years with less than median rainfall. The combined impacts of drought and over-allocation of water for irrigation use have led to severe stress on floodplains and wetlands. Climate change projections suggest that the Murray-Darling Basin will be on average drier in the future. The recent drought period has experienced lower autumn and winter rain and higher temperatures than past droughts, resulting in the lowest runoff totals on record in recent years. While these features may be associated with climate change, they may equally be a result of large, long-term climate variability. The recent drought and declining river health have exposed the inadequacy of current water management to cope with the variability of water availability in the Murray-Darling Basin. Future water management strategies should involve consideration of a range of scenarios, including those incorporating climate change.

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16.1 Introduction

Australia is, in the words of one of the country's best loved poems, a land "of drought and flooding rains".[1] Drought, often associated with El Nino events, is interspersed with wetter periods. Australia experiences a major drought about once every 10 years (Bureau of Meteorology 2004).

The southeastern part of Australia, including the Murray-Darling Basin (shown in Fig. 16.1), has recently experienced a drought more severe than any previously experienced (Timbal 2009). The drought is compounded by water diversions, which by about 1995 had risen to nearly half of the water resource available in an average year in the Murray-Darling Basin. The consequent decline of water available to the environment has led to declining river health (MDBC 2002), which has been much exacerbated in the last few years of drought. In 2002, the Murray-Darling Basin Commission (MDBC) reported that the average annual discharge to the sea from the Murray had fallen to 27 % of its natural, pre-development value (MDBC 2002). For the last few years, the discharge has been effectively zero: the lower lakes, which are separated from the sea by a series of barrages are now about 0.8 m below sea level, and expected to fall to more than 1 m below sea level over the summer (MDBA 2009). The health of the floodplain and wetlands continues to decline, with the lower part of the Murray having experienced 13 years at the time of this writing without a significant flood (many ecosystems depend on periodic floods).

The responses to the declining river health and rising diversions have included: a cap on diversions since 1995 (MDBA 2009); water reform under the National Water Initiative, particularly market-based measures, to increase the efficiency of use and provide for greater certainty for investment and for the environment (NWC 2009); and the Water for the Future plan of the Commonwealth Government which, amongst other things, aims to restore water to the rivers by upgrading leaky irrigation systems and acquiring water entitlements to provide water for the environment (DEWHA 2009). The policy and economics of these responses are covered in other chapters in this book.

The aims of this chapter are to set the hydrological scene: to characterize historic droughts, to compare the recent drought, and to show scenarios of possible future droughts under climate change. We also aim to identify some hydrological limits to policy and management—what is possible and what is not. The scope of the chapter is surface water resources, which are most immediately affected by drought.

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[1] A line from "My Country," by Dorothea Mackellar, first published in 1908.

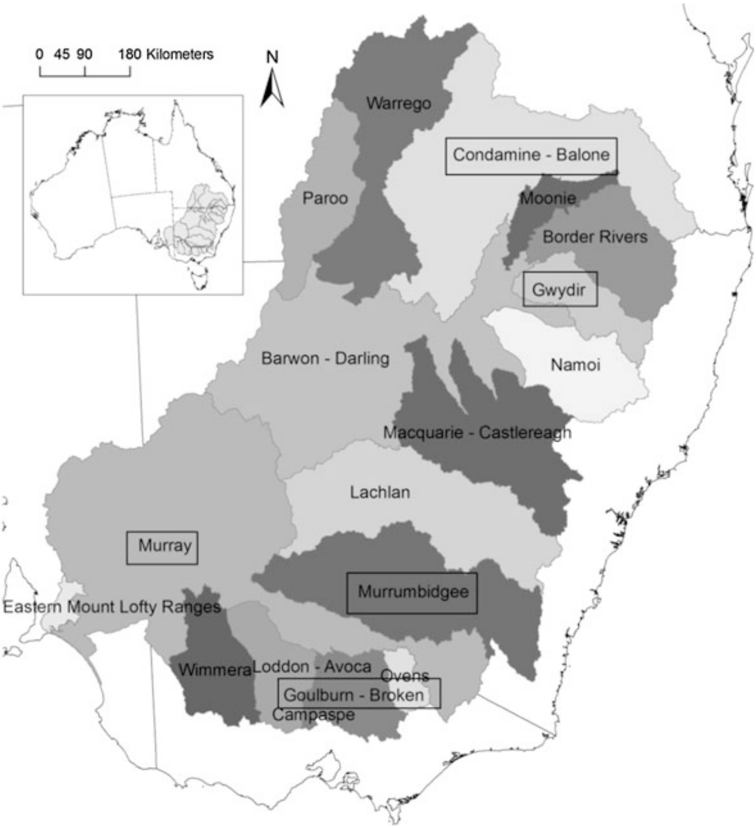

Fig. 16.1 The Murray-Darling Basin, with the regions used in the CSIRO sustainable yields project. The five regions described in this chapter are shown in *boxes*

16.2 What do We Mean by Drought?

We outline some general features of Murray-Darling Basin rainfall in Fig. 16.2. The figure shows the whole Murray-Darling Basin annual rainfall (i.e., the spatial average of annual totals). Superimposed are a five-year moving average, and averages for earlier and later periods showing the well-known drier first part of last century and the wetter later part (until 1995, or so). Also shown is the median rainfall for the whole period, and the droughts that are generally considered as major droughts in Australia (Bureau of Meteorology 2004). All of the droughts have a long run of years below the median, or a year well below the median, or both.

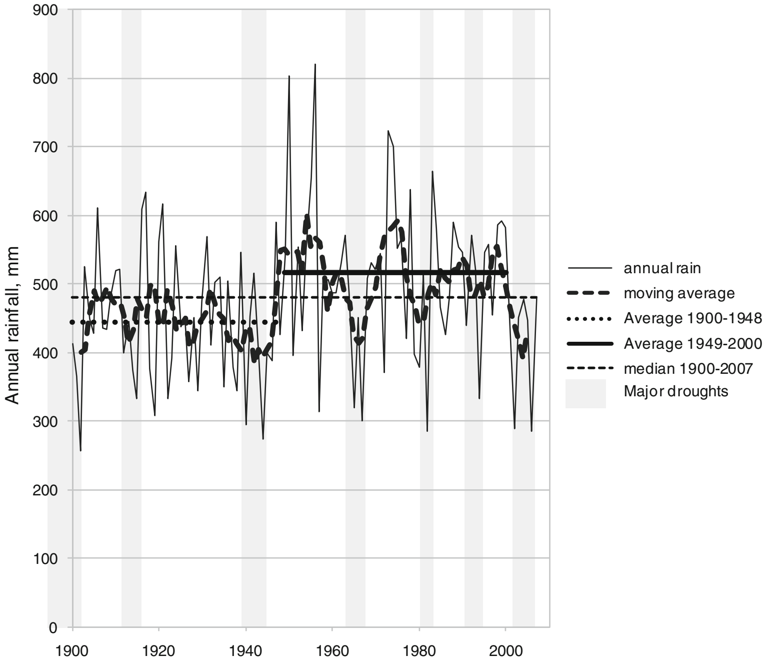

Fig. 16.2 Spatially averaged annual rainfall for the Murray-Darling Basin. *Sources* Rainfall record, Hennessy et al. (2008); drought periods (*vertical stripes*), Bureau of Meteorology (2004)

16.2.1 Some Simple Metrics: Long, Dry Periods

The aim in this chapter is to build upon the information gleaned from the Murray-Darling Basin Sustainable Yields (MDBSY) project[2] results and look more comprehensively at the dry years and, in particular, at runs of dry years. There are several drought indices, and different ways of defining drought. Hounan (1976) notes that perceptions of drought differ among meteorology, agriculture, hydrology, and economics, and lists 29 indices relevant to meteorological and agricultural drought. Maher (1973) suggests that a generally acceptable, though nevertheless inadequate, definition is “severe and prolonged water shortage.” We

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[2] The Murray-Darling Basin Sustainable Yields project was a major project commissioned by the Australian Federal Government, and undertaken by CSIRO in association with relevant state agencies and leading consultants (See Kendall et al. for further details). The project assessed water availability in the Murray-Darling Basin under four main scenarios: historic climate, the current severe drought, climate change (with dry, median and wet sub-scenarios), and climate change plus some anticipated developments which could change water availability (but which did not include changes to the locations or allocations of irrigation water use). The project modeled the water availability under current rules of water sharing, and linked surface water and groundwater use. The project was completed in 2008, the results of which are available in a series of reports (CSIRO 2008).

make use of this definition, but rather than appealing to a single index of drought, we work directly with the length and severity of dry periods, where the severity is defined as a departure (on the dry side) from the median.

We chose five regions from the MDBSY project as a north–south transect: Condamine, Gwydir, Murrumbidgee, Murray and Goulburn (Fig. 16.1). For each region, we examined the modeled runoff for the headwater regions above the major dam or dams (respectively: Chinchilla Weir; Copeton; Burrinjuck and Blowering; Hume and Dartmouth; Eildon), dam storage levels, diversions and end-of-system flows. For the Murray, we also examined the flows at an intermediate point (Wakool). We examined the full length (111 years) of the MDBSY modeled results, for the historical and three main climate change scenarios—a median projection and a wet and a dry extreme.

The MDBSY modeled climate change projections were obtained by scaling the historic climate sequences. The scaling was performed to vary historical daily and seasonal rainfall (and other climate variables) to match their distribution in the IPCC AR4 modeled rainfall (or other climate variables), while preserving the overall annual totals (or averages) expected in 2030 in the IPCC results. The key point for this study is that the sequences of rainfall are given by the historical records being scaled. Droughts, therefore, occur in the same sequence and have the same general order of severity (that is, the deepest drought in the record is the most recent, and the deepest in the modeled scenarios is that at the end of the modeled period). Other forms of climate change projection will result in drought results that differ from those presented here.

16.2.2 Length of Dry Runs

For every region and measure (runoff, flows, etc.) and the historical scenario, the first step is to identify the median value for the 111-year record. The next step is to identify all years that are drier than the median, and to count how often there are 1, 2, 3, 4, etc. dry years in a row (i.e., a run unbroken by a year wetter than the median). This is done for the historic and climate change scenarios, always with reference to the median of the historic scenario. Thus we identify in our future projections whether there are fewer or more dry runs than in the historic record, and whether the runs are longer or shorter.

To illustrate the steps so far, Fig. 16.3 shows the modeled historic runoff record for the Condamine, and Fig. 16.4 shows the analogous record for the dry climate scenario. By inspection, it can be seen that there are more dry years (years with runoff less than the historic median) in Fig. 16.4 than in Fig. 16.3, and that the runs of dry years are longer. (We may also note that the runoff reflects the generally drier period in the first part of the record and the generally wetter period in the second part of the record. All regions and measures reported here show this general pattern.) Figure 16.5 plots the frequency of the dry runs, and shows that there are more single dry years in the historic scenario, but more long runs of dry

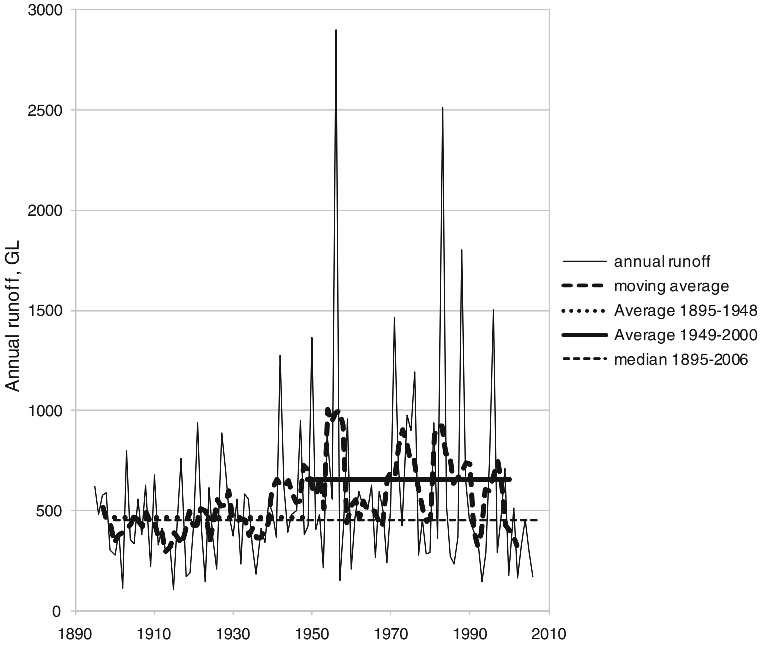

Fig. 16.3 Modeled historic runoff for the Condamine above Chinchilla weir

years (particularly runs of 5 years or more) in the dry extreme and median climate change projections. For ease of presenting the information, we will hereafter refer mainly to the number of runs of 5 years or more, which for the runoff in the Condamine are one for the historic scenario, five for the dry extreme, three for the median, and one for the wet extreme projection.

The total number of years in the 111-year Condamine sequence in runs of 5 years or more is six for the historic scenario, 28 for the dry extreme, 16 for median, and six for the wet extreme projection.

The two numbers above—number of runs of 5 years or more, and total number of years in the 111-year sequence in runs of 5 years or more—are calculated for all regions, scenarios and measures (runoff, flow, etc.), and together indicate the length of long dry runs.

16.2.3 Severity of Dry Runs

To indicate the severity of a dry run, we calculated the average reduction of the measure in a run of dry years. The average reductions in runoff for dry runs are plotted in Fig. 16.5 as percentages. The average reductions in runs of dry years of 5 years or more are taken to indicate the severity of long dry runs.

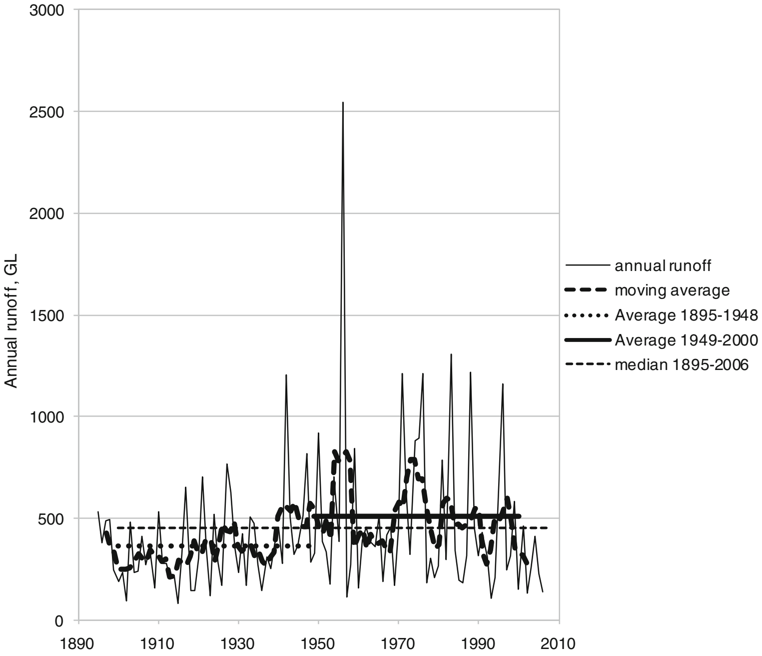

Fig. 16.4 Modeled dry extreme climate change runoff for the Condamine above Chinchilla weir (based on scaling the historic rainfall, and presented as if for the same years as the historic modeled period in Fig. 16.3). The median is the historic median (i.e., the same as in Fig. 16.3)

16.3 Past, Present and Projected Droughts in the Murray-Darling Basin

16.3.1 Historic and Projected Droughts: Length and Severity

Figure 16.6 shows the results for runoff. The top two charts show that:

- there is a general trend to lengthier long dry runs going from the Condamine in the north to the Goulburn in the south (that general trend is reversed in the Gwydir and the Murrumbigee);
- long dry runs in dry extreme and median climate change projections are projected to be longer, more frequent or both than those in the historic scenario, strongly so in the case of dry extreme, and in all regions;
- the long dry runs in the wet extreme scenario are of the same length as those in the historic scenario for all regions (except in the Murrumbidgee); and
- the Murrumbidgee has no dry run of five or more years in the wet extreme scenario.

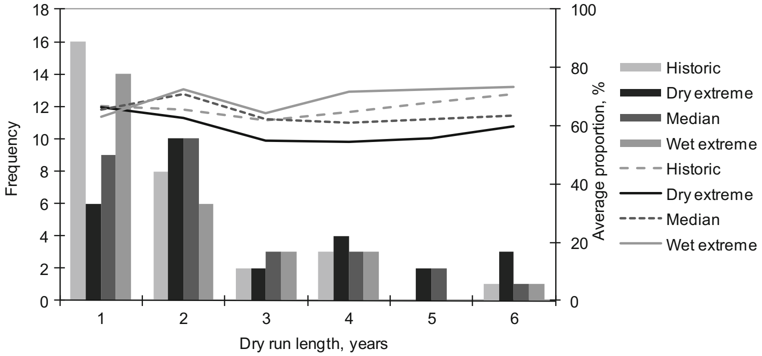

Fig. 16.5 Frequency of runs of dry years of different length, and average proportion of historical median (as a percentage) for each run of dry years, for runoff in the Condamine region

In terms of the severity, Fig. 16.5 shows the average reduction in modeled runoff was greatest for the dry extreme scenario, followed by the median projection and historic scenarios, and least for the wet extreme scenario. The average reduction in any scenario did not vary greatly with the length of the dry run.

The bottom part of Fig. 16.6 shows that, for runoff:

- there is no particular north–south trend in severity in the historic, median, or wet extreme climate change scenarios;
- the dry extreme scenario indicates more severe long dry runs in the south (with a reversal from the Gwydir to the Murrumbidgee);
- in the dry extreme and median climate change scenarios, long dry runs are more severe than the historic for all regions except the Gwydir; and
- the wet extreme projection long dry runs are less severe than the historic for all regions except the Goulburn.

This general pattern was repeated for dam storages, diversions and end of system flows (except that the general north–south trends of increasing length and severity are not reversed at Gwydir–Murrumbidgee for these measures). What differed with these other measures was the size of the average reduction (i.e., how much less water was stored, diverted or flowed, compared to the reductions in runoff).

Figure 16.7 shows the average reductions during long dry runs in storage, diversions and flows. Whereas modeled runoff was generally reduced to between about 50 and 75 % of the median historic value, storage was reduced to between about 35 and 70 %, and flows to between about 20 and 70 %. The reduction in modeled end-of-system flows is particularly pronounced in the Murray, Murrumbidgee, and Goulburn. Flows at the intermediate point on the Murray, at Wakool, were reduced to between about 60 and 70 %. Generally, then, the reduction in flows were greater than the reduction in storage, which in turn were greater than the reduction in runoff. van Dijk et al. (2008) showed this pronounced

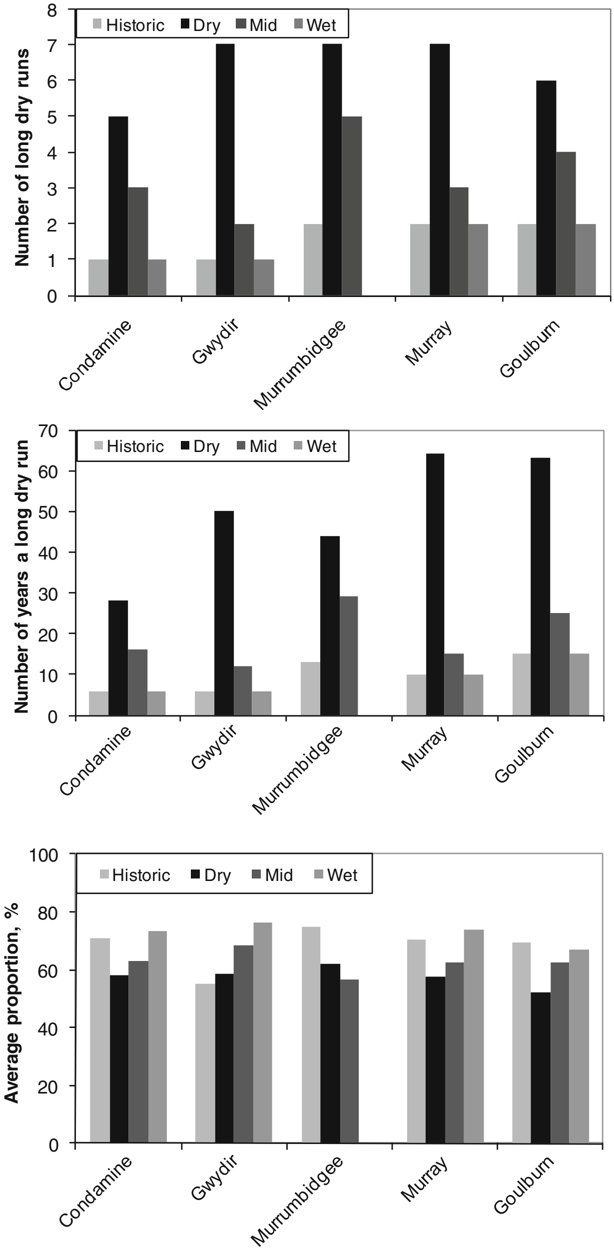

Fig. 16.6 Runoff in long dry runs: *top*—number of long dry runs; *middle*—total number of years in 111 in a long dry run; *bottom*—average proportion of the median historic value in long dry runs. A long dry run is a dry run of 5 years or more

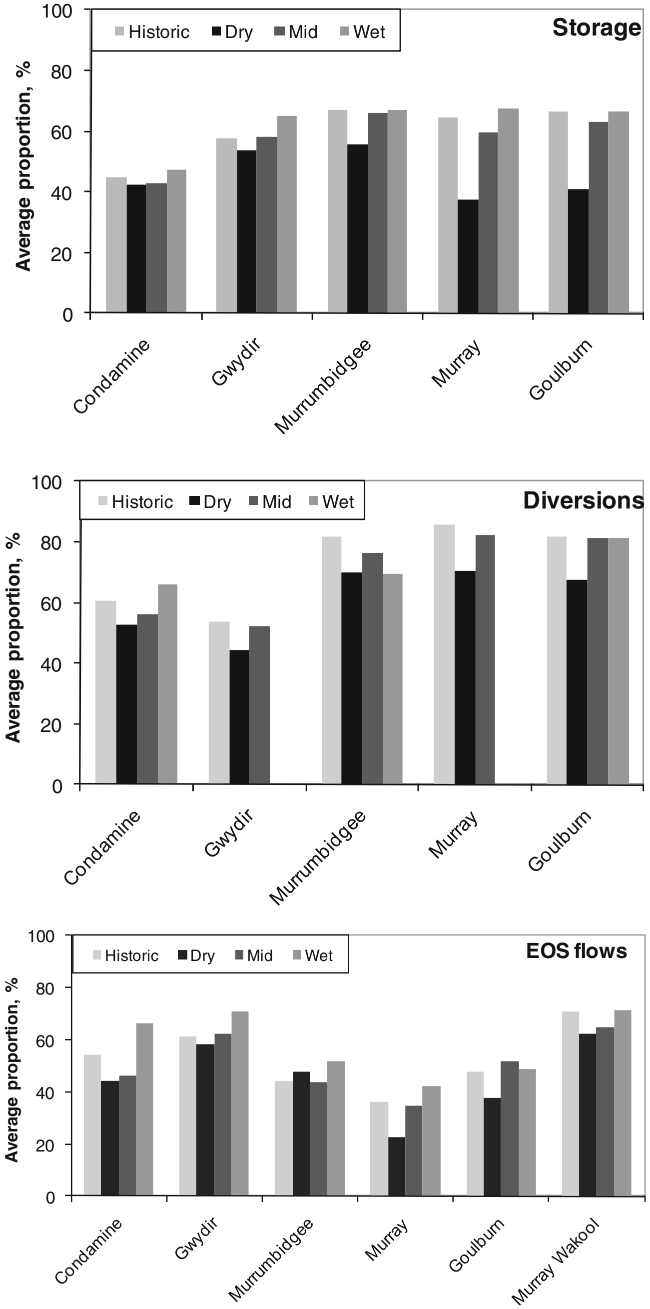

Fig. 16.7 Average proportion of the median historic value in long dry runs: *top*—storage; *middle*—diversions; *bottom*—end-of-system flows, plus the flow at Wakool, an intermediate point on the Murray

effect on flows and lesser effect on diversions for all of the regions in the Murray-Darling Basin for average (not drought) conditions in the MDBSY results. We discuss the reasons for this in the section “Rainfall, runoff, river flows and diversions” below.

The behavior of the modeled diversions differed, however, particularly in the south of the basin (Murrumbidgee, Murray, and Goulburn). The modeled reduction in diversions (using the assumption of current water-sharing rules) in these three regions was between about 70 and 85 % of the median, somewhat less than the reduction in runoff. This is consistent with a general finding of the Murray-Darling Basin Sustainable Yields study (reported for all years, not just drought years) (CSIRO 2008; Young and Chiew 2009), that the current rules of allocation and diversion shelter irrigation from the impacts of reductions in water availability.

16.3.2 The Recent Drought

The recent drought was the worst in the last 110 years (Timbal 2009), which is the period of high-quality records available for such comparisons.

A significant feature of the recent drought is the greater temperatures than those experienced in past droughts (Murphy and Timbal 2007), and the seasonal pattern of the reduced rainfall (Timbal 2009). In addition, inflows into the River Murray in the last 10 years have been about half the historic average (MDBA 2009, and Fig. 16.8), and those in 2006 were considerably less than the previous historic minimum. Inflows during the main inflow period from June to October were in 2006 less than 10 % of those in the long-term mean. Note that reduction in runoff for the worst single year of the recent drought is not comparable to the average reductions over a run of dry years shown in the bottom plot in Fig. 16.6.

Figure 16.9 shows the anomaly (departure from the long-term mean) in the annual mean temperature, averaged across the Murray-Darling Basin (Hennessy et al. 2008). The temperature anomaly (and therefore the actual mean temperatures) has risen over the last few decades, and is now about 1 °C greater than the long-term mean.

Figure 16.10 shows the mean monthly rainfall and runoff averaged over the southern Murray-Darling Basin (Potter et al. 2008) for 1895–2006, and for three 10-year dry periods. During the recent drought, the greatest reduction in rainfall was during the autumn and early winter, whereas the earlier dry periods had reduced rainfall spread more throughout the year (Fig. 16.10a). This has led in the recent drought to soils being less saturated, and subsurface water storage being lower, at the start of the winter. Consequently, the winter rain in the recent drought mostly just refilled the soil, with little being leftover for runoff. Since winter and early spring are the periods of greatest runoff (Fig. 16.10b), the reduction during these periods has a disproportionate effect. Thus, the recent drought has seen reductions in runoff greater than those in previous dry periods (Potter et al. 2008, and Fig. 16.10b). Potter and Chiew (2009) show that, for the Campaspe region in

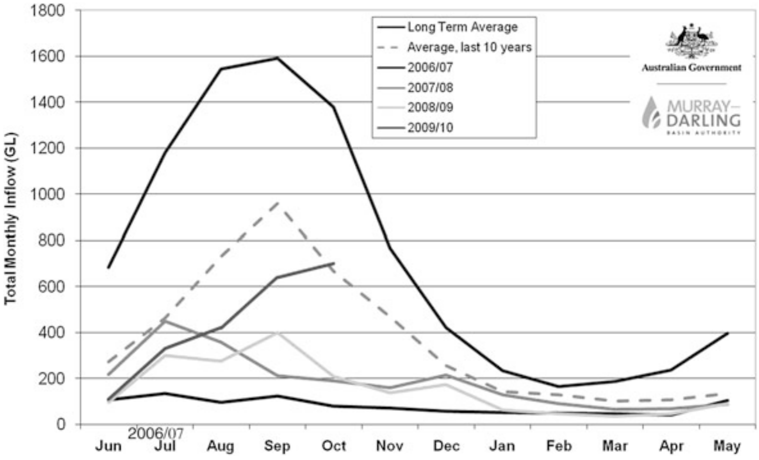

Fig. 16.8 Murray system inflows (excluding Snowy and Menindee inflows). *Source* MDBA (2009)

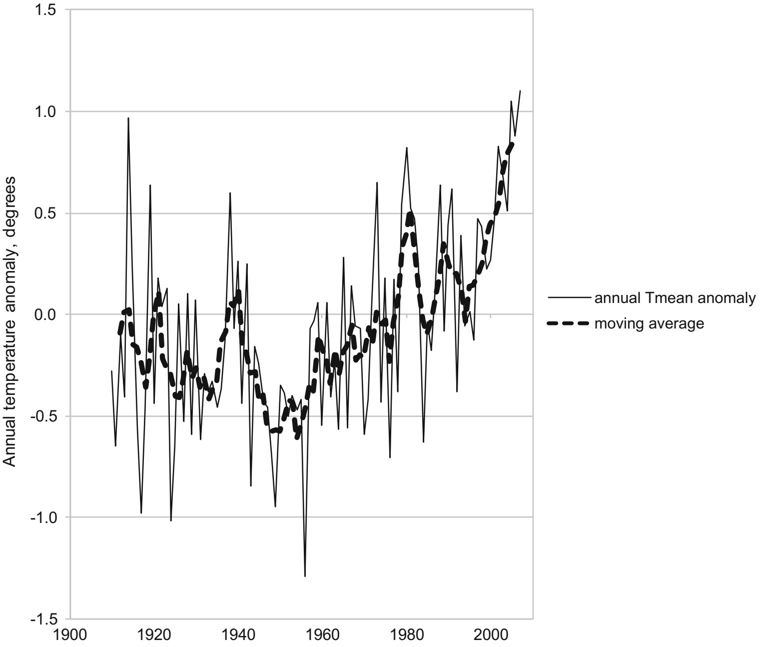

Fig. 16.9 Annual temperature anomaly (departure from the 1961–1990 mean) for the Murray-Darling Basin. *Source* Hennessy et al. (2008)

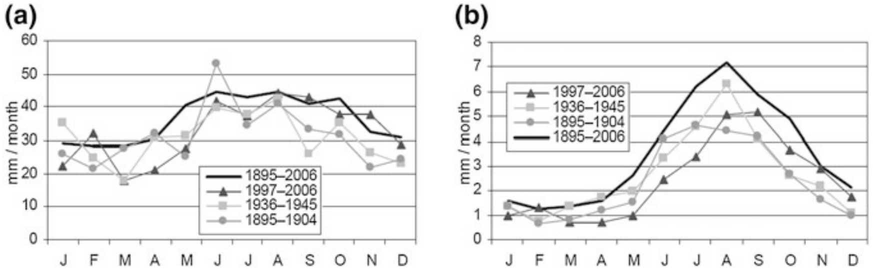

Fig. 16.10 **a** Monthly rainfall and **b** monthly runoff for the southern Murray-Darling Basin averaged across selected time periods. *Source* Potter et al. (2008)

the south of the Murray-Darling Basin, the reduction in runoff was caused primarily by the reduction in mean annual rainfall, followed by the changed seasonality and lack of high rainfall years in the past decade, then by the change in evapotranspiration (related to the elevated temperatures).

We made use above of the Murray-Darling Sustainable Yields project results of modeled runoff, storages, diversions, and flows, which were for the years up to 2006. We have modeled these results for the Murray alone up to 2009, to show the extreme nature of the recent drought (Fig. 16.11). All four measures drop in 2006 below the previous record low. We discuss this further in the next section.

Chiew et al. (2009) review evidence whether the current drought was associated with global warming, and conclude that it is not currently possible to separate a global warming signal from large, natural, long-term climate variability. Thus, the drought could be associated with a global warming, or a return to the conditions of the first half of the last century.

16.4 Rainfall, Runoff, River Flows, and Diversions

Decreased rainfall leads to decreased runoff, which in turn leads to decreased river flows. In Australia, in common with other arid and semi-arid environments, the decreases are amplified: the decline in runoff varies from 2 to 3.5 times the decline in rainfall (Chiew 2006).

Raupach et al. (2009) show that the average flow at the River Murray at Wentworth has, since 2002, been 23 % of its pre-2002 value. They conclude that this results mostly from a decline in the fraction of rainfall that becomes runoff (to 41 % of its earlier value), followed by a decline in the fraction of runoff that reaches the river gauge (i.e., an increase in fractional losses in the river system) (to 68 %), followed by a decline in the rainfall (to 81 %). We showed above, and in Figs. 16.6 (bottom) and 16.7 that the reduction in modeled flows was greater than that in runoff, consistent with the amplification noted by Raupach et al. (2009). The result is also consistent with the amplification factors given in van Dijk et al. (2008) for average conditions.

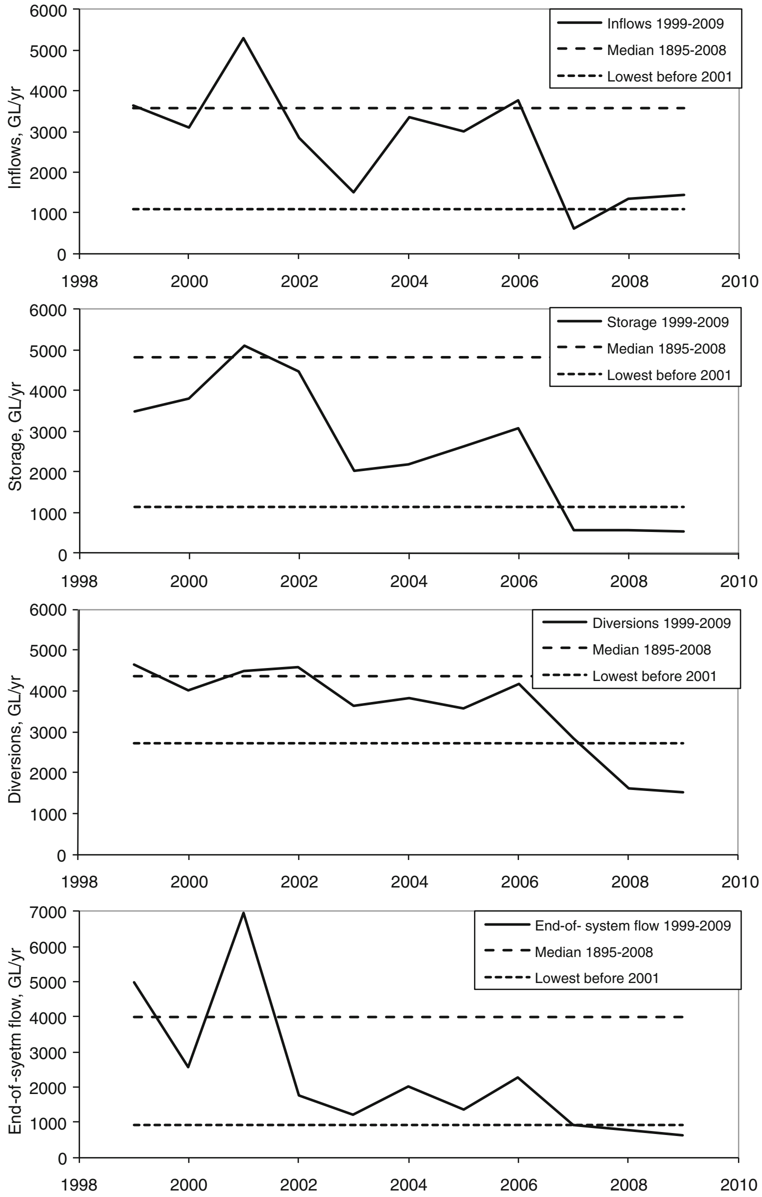

Fig. 16.11 Impact of the current drought on the River Murray: top, inflows to the Hume and Dartmouth reservoirs; middle top, storage volumes in the Hume and Dartmouth reservoirs; middle bottom, diversions; bottom, flows at the end of the system (Lock 1). The year is the year to the end of June—thus 2007 is the year July 2006 to June 2007

The amplification of rainfall declines into runoff declines are mostly a result of the hydrology of the situation—in drier landscapes and drier times, natural water storages (in the soil, the subsoil, wetlands, and so on) dry out more, so a greater proportion of the rain may be retained and become evapotranspiration, leaving less to runoff. The amplification of runoff declines to river flow is partly a result of the hydrology—in a flat, arid landscape, rivers lose water to evaporation and seepage—and partly a result of managed diversions.

The reductions in diversions in the south of the basin, in contrast, were less than the reductions in the runoff. This is solely a result of the current rules of water sharing, and the way the rules allocate water to irrigation. The impact of the water-sharing rules is also seen in Fig. 16.11. The irrigation diversions showed little response to the lower inflows in 2003, because the reservoir storage levels were adequate to maintain supplies; the end-of-system flows, however, dropped dramatically. The 3 years from July 2004 to June 2006 saw inflows approaching the long-term median (slightly above in 2005–2006), sufficient under the water-sharing rules to supply irrigation at near median levels, but insufficient to either refill the reservoirs or provide for flows (Fig. 16.11). Finally, the unprecedented dry year of 2006–2007 saw storage levels, diversions, and flows fall to considerably less than their previous minimums. Hayman and McCarthy (2010) describe how this led to the first "irrigation drought" for irrigators near the downstream end of the system.

16.5 Implications for Policy and Management

The experience of the recent drought, the knowledge of the long-term cycles of water availability over the last 110 years or so, and the projections for climate change, have serious implications for the future management of the rivers and irrigation of the Murray-Darling Basin. The over-riding conclusion is that current water management approaches are inadequate to deal with the high variability in water availability (Chiew et al. 2009). Neither the irrigation sector nor the environment can be sustained at desired levels in droughts as severe as the recent one or those that we may expect in the future. New water sharing arrangements are the subject of much debate at the time of writing.

The recent drought had features absent in previous droughts. It is possible that the dominant hydrological processes may have changed: the connections between surface water and subsurface stored water may have been lost, such that rainfall amounts that historically would have led to runoff appear now to lead to little or no runoff (Chiew et al. 2009). Milly et al. (2008) explored this issue in greater detail. Thus, policy and management are best developed for scenarios that describe a range of possible futures (Chiew et al. 2009), and should not rely solely on past experience.

Projected future dry runs are longer and more severe in the median and dry extreme scenarios than those in the historic record, so if these scenarios are realized in the future, it is likely that there will be future droughts **worse** than the recent drought. A return to the drier conditions in the first half of last century, even in the absence of global climate change, would lead to long dry runs that are longer and more severe than those in the second half of last century. A combination of the drier conditions in the first half of last century with global climate change would lead to long dry runs that are very long and severe by historic standards. In the Goulburn region in particular, the situation would, by historic standards, be more or less a perpetual drought in the dry extreme scenario.

The projected increase in long dry runs affects the flows (and hence the prospects of maintaining river health and other flow-dependent environmental assets) and the storages and diversions. In the recent drought, there was insufficient water for either the environment or irrigation. This situation would be exacerbated under projected climate change. The situation would also be exacerbated should there be a return to the drier conditions in the first half of last century.

The current management rules for operating the river and allocating water favor irrigation over the environment (although this appears not to be the intent of various water acts). Changing this requires a change in management or ownership by an environmental agent of entitlements (which is envisaged under the Water for the Future plan; DEWHA 2009).

16.5.1 Options for Dealing with Drought: Some Hydrological Constraints

Looking to options to deal with droughts, we leave economic and policy considerations to the other chapters in this book. Here, we comment on some hydrological possibilities.

- Larger dams would be irrelevant in the projected longer and more severe long dry runs.
- Migration of irrigation downstream, if the current (slow) trend were to result in similar volumes of water being used as at present but further downstream, would overall leave irrigation vulnerable to projected longer and more severe long dry runs. This is because river losses are greater in dry years, as shown by the more severe declines in flows at the end of the River Murray than at Wakool (Fig. 16.7).
- Conversely, migration of irrigation upstream such that similar volumes of water were used as at present but further upstream (closer to water storages) would leave irrigation somewhat less vulnerable to projected longer and more severe long dry runs. This is because river losses are less at upstream locations, and also because rainfall is higher so less irrigation is required (for a given crop, soil, etc.). However, this would also leave less water in the river for flows downstream. In any event, other factors (primarily economic) are driving irrigation

downstream. Any provision of water to downstream environmental assets would also mean there is little to gain under this strategy.

- Improving irrigation canals to minimize leaks and improve conveyance efficiency (one strategy under the Water for the Future plan, DEWHA 2009) is appealing, but is not equally effective under all circumstances. The leaks all go somewhere. There is little gain from stopping a leak that returns water to the river or some other use, although there are gains from stopping leaks to saline or otherwise unusable groundwater, and from reducing evaporation. Qureshi et al. (2009) show that return flows significantly diminish the economic benefit of infrastructure improvement.
- Purchasing access entitlements may be more effective (Productivity Commission 2009; Qureshi et al. 2009), and are most effective when they take account of where the water is required (Mainuddin et al. 2007). This is because losses of water from the river (through seepage or evaporation) can render an acquisition less effective than another, seemingly more expensive, purchase. As discussed by Mainuddin et al. (2007), acquisition strategies sometimes leave this factor out.
- Improving irrigation efficiency, such as changing from flood to drip irrigation, can lead to greater irrigation productivity from less water. However, it may also diminish return flows, leading again to the problem noted above of diminished water to the river and diminished benefit (Qureshi et al. 2009).
- There may be opportunities to manage environmental water more effectively to achieve multiple targets. Thus, an environmental flow might be used to both water some flood-dependent wetlands and reduce salinity in a sensitive stretch of the river.

16.6 Conclusions

The recent drought exposed the inadequacy of our water policy and management: current arrangements cannot deliver water to both irrigation and the environment at desired levels in droughts like the recent one. We cannot return water to the environment and keep irrigation going in its current form. New water sharing arrangements are the subject of much debate at the time of writing.

The recent drought was in some ways comparable to extreme droughts in the past, but also contains some features that suggest, but do not prove, that climate change may be influencing southeastern Australia. More importantly, these features show that past droughts do not provide a sufficient guide to future management: a range of scenarios including climate change scenarios must be considered.

Policy and management should be prepared to cope with future droughts more severe than that which we recently experienced. Climate change projections are uncertain, and climate variability will no doubt result in wet and dry periods, but such preparations are prudent and will leave us able to cope with whatever the future holds.

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Chapter 17
Climate Change Impacts on California's Water Resources

Ali Mirchi, Kaveh Madani, Maurice Roos and David W. Watkins

Abstract While California's water resources and infrastructure are already facing critical challenges in terms of providing Californians with adequate water supply, numerous studies have demonstrated the unfavorable impacts of climate change on the state's water supply system. As such, observed temperature increases, changing precipitation patterns, variations in runoff timing and magnitude resulting from changes in snow accumulation and melt characteristics, and recent droughts in California may be partly attributable to changing hydro-climatic conditions. Hence, from a water supply standpoint, the study of climate change and consequent hydrologic variability bear important implications for water resources planning and management in California. This chapter aims to illustrate how climate change and its associated impacts have affected or are expected to affect California's water resources. Additionally, implications for water infrastructure and a summary of strategies for adaptation to climate change are presented.

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17.1 Introduction

There are extensive, unequivocal indications that climate is changing at global and regional scales. A comprehensive analysis of the enormous body of observations pertaining to disparate parts of the climate system by the Intergovernmental Panel on Climate Change (IPCC) demonstrated that global warming is indeed occurring (IPCC 2001, 2007). Since 1900, the global average temperature has increased by about 1.5 °F(0.8 °C) and is projected to rise another 2.5–10.4 °F(1.4–5.8 °C) by 2100 (IPCC 2001). Distressingly, it is very likely that the United States' average temperature will rise even beyond the global average (Karl et al. 2009). In California, numerous studies have demonstrated the changes in amount and timing of streamflows that are largely attributable to changes in temperature trends, precipitation forms, and snow accumulation and melt characteristics (Roos 1987, 1991; Wahl 1991; Aguado et al. 1992; Dettinger and Cayan 1995; Shelton 1998; Cayan et al. 2001; Stewart et al. 2004, 2005). These observations are in agreement with global evidences of a warming world.

California's water infrastructure is already encountering crucial complications in terms of providing sufficient water supply in the face of hydrological variability coupled with socio-economic dynamics. The state relies on three major water supply sources, namely surface water and snowmelt runoff stored in reservoirs, groundwater, and transbasin supplies (Table 17.1). Approximately 75 % of California's available water supply originates in three hydrologic regions (of 10 regions in the state) in the northern basins comprising one-third of the state's land area (CNRA 2009), yet 80 % of the demand occurs in the southern two-thirds of the state. Nearly all of California's principal sources of water supply are currently utilized at full capacity (Wilkinson et al. 2002). For example, the Central Valley Project (CVP) and the State Water Project (SWP), the two largest components of water supply system in California, collectively supply water to more than 20 million people and irrigate approximately 3.75 million acres of agricultural land. Hence, from a water supply perspective, the study of climate change and consequent increased hydrologic variability bears important implications for developing climate change adaptation strategies.

Table 17.1 Average annual water supply [in million acre feet per year (MAF/yr)] in California (Adapted from Wilkinson et al. 2002)

Supply source	MAF/yr
Reservoir storage capacity	42.8
Surface water extraction	21.6
Groundwater extraction	15.0
Delta extraction	10.3
Colorado river imports	5.2
Local imports	1.0
Reclaimed water	0.2
Desalinated water	0.017

The climate and hydrologic conditions of California are geographically variable, potentially making the state more susceptible and vulnerable to climate change (Vicuna et al. 2007; Diffenbaugh et al. 2008). Pronounced spatial and temporal fluctuations in California's precipitation have historically translated into a series of floods and droughts in the state. It is likely that climate change will further exacerbate the frequency and magnitude of these phenomena. This chapter provides an overview of how climate change has impacted or will impact the hydrologic cycle in California, thereby affecting the state's water supply. First, the observed and potential hydro-climatic impacts of climate change in California, such as rising temperatures, alteration of snow accumulation and melt characteristics, precipitation and runoff patterns, droughts, and sea level rise are discussed in a water supply context. Then, we discuss the implications of climate change for California's water supply infrastructure, along with a summary of strategies for adaptation to climate change.

17.2 Hydro-Climatic Impacts of Climate Change on California

Many researchers have studied the hydro-climatic impacts of climate change on California (Vicuna and Dracup 2007) by running General Circulation Models (GCMs) (CCSP 2008) under the IPCC Special Report on Emissions Scenarios (SRES) (IPCC 2001). The IPCC (2001) introduced four emissions scenario families (A1, A2, B1, and B2) that address potential development trajectories, based on predefined demographic and economic changes, technological advancements, and environmental impacts of changing carbon dioxide concentrations in the atmosphere. The A1 scenario is further divided into three groups, depending on the type of energy source used for technological development. These climate change storylines are widely used for providing inputs in climate change vulnerability and impact assessments including the most recent IPCC assessment report (IPCC 2007). The projected hydro-climatic changes are then downscaled to serve as inputs to statistical and physically based models to determine regional changes in the components of the hydrologic cycle (Vicuna and Dracup 2007). Table 17.2 presents a list of SRES storylines and their underlying assumptions.

Climate change is gradually altering California's hydrology, posing considerable challenges for water resources systems. With an increasing trend in temperature levels and subsequent changes in snow accumulation and melt pattern, the timing of runoff will continue to shift to earlier in the water year (Vicuna and Dracup 2007), and flows will likely be lower in summer. Furthermore, climate change will affect surface water quality and groundwater resources, placing additional burdens on the state's already stressed water supply system. As regional and seasonal precipitation patterns change, extreme events such as floods and droughts are expected to become more frequent and will likely have higher magnitudes, which will potentially impact all components of California's water infrastructure,

Table 17.2 SRES storylines and their underlying assumptions (*Source* IPCC 2001)

Scenario	Description
A1	Very rapid economic growth, mid-century peak global population, rapid introduction of new and more efficient technologies
A1FI	Intensive use of fossil fuel resources to drive technological changes in A1
A1T	Use of non-fossil fuel resources to drive technological changes in A1
A1B	Balanced use of all energy resources to drive technological changes in A1
B1	Same global population as A1, but with more rapid changes in economic structures toward a service and information economy
B2	Intermediate population and economic growth with local solutions to economic, social, and environmental sustainability
A2	Very heterogeneous world with high population growth, slow economic development and slow technological change

including reservoirs, conveyance systems, and treatment facilities (Wilkinson et al. 2002). The growing body of evidence for climate warming implies that the past century's water system management and development practices may not be a reliable guide for the future. In this section, a synthesis of observations of climate change and its effects on California's hydrology is presented.

17.2.1 Temperature

Although California's natural climate variability, ranging from arid to subarctic, has contributed to heterogeneous climate change at local scales, the state's overall average temperatures have been rising over much of the past century (Bonfils et al. 2007; Pittiglio et al. 2008; Cayan et al. 2009). The trend of mean temperature rise in California's inland rural areas seems to be slower than the global trend, suggesting that the significant impact of the urban heat effect is counterbalanced to some extent by summer cooling due to inland irrigation. Nevertheless, observations near the ocean, even in rural areas, show a rise in average temperature during the 1980s and 1990s (Roos 2001). At a regional scale, while the step-like temperature rise of the 1970s and 1980s has flattened out since then, the minimum winter temperatures have continued to rise somewhat (Fig. 17.1). Bonfils et al. (2007) showed that the warming of California's winters over the second half of the twentieth century is associated with anthropogenic atmospheric changes. As shown in Fig. 17.1, mean winter temperature departure time series for California's south coast region, produced by Western Regional Climate Center, shows a temperature increase of more than 1 °F (more than 0.5 °C) during the past century (WRCC 2011). Likewise, by considering 16 climate zones established by the California Energy Commission, Pittiglio et al. (2008) found an increase in the annual minimum area-weighted temperature averaged over the state of California during the period 1920–2003. Figure 17.2 shows GCM-predicted trends of temperature rise during the past and present centuries (Cayan et al. 2009). Thus,

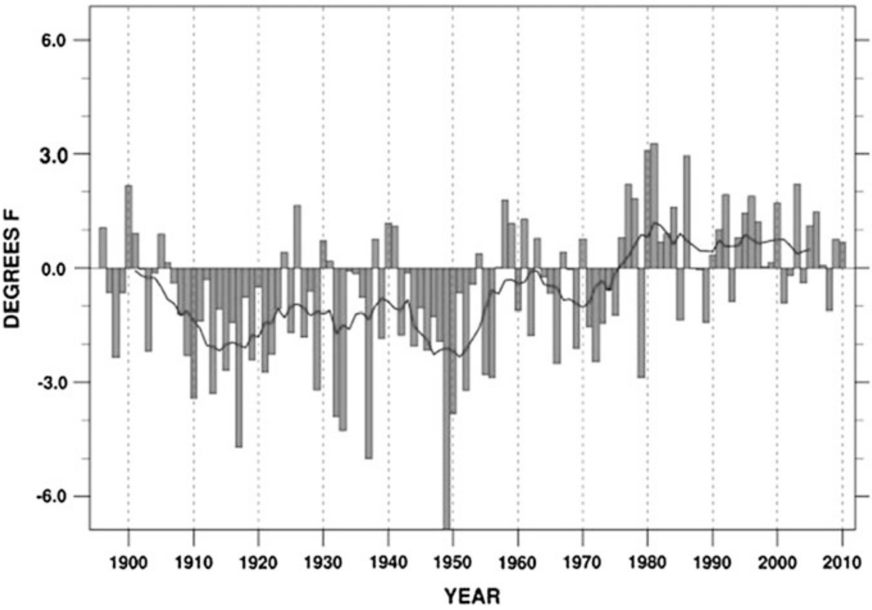

Fig. 17.1 Mean winter temperature departure time series for California's south coast region; *black line* shows 11 year running mean departures from 1949 to 2005 reference periods (*Source* WRCC 2011)

although any precise quantification of the present trend and future projections of statewide temperature rise may be highly questionable, recent studies raise legitimate concerns about the potential impacts of regional climate warming on California's water resources. Rising temperatures could significantly affect a number of hydrologic processes, and subsequently water supplies, across the state (Mote et al. 2005).

17.2.2 Snowpack

While the state's total reservoir storage is around 43 MAF[1], the average snowpack volume in California is estimated at about 15 MAF. Over the twentieth century, the average early spring snowmelt runoff has decreased by about 10 %, a loss of 1.5 MAF of water (Roos 1991). Results of the work by Cayan et al. (2009) suggest that the current trend of climate warming in California is likely to continue. This trend may significantly alter the northern basins' snow hydrology, manifested by the snowline gradually moving higher and reducing the Sierra snowpack.

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[1] The largest surface reservoir is Shasta with storage capacity of 4.5 MAF.

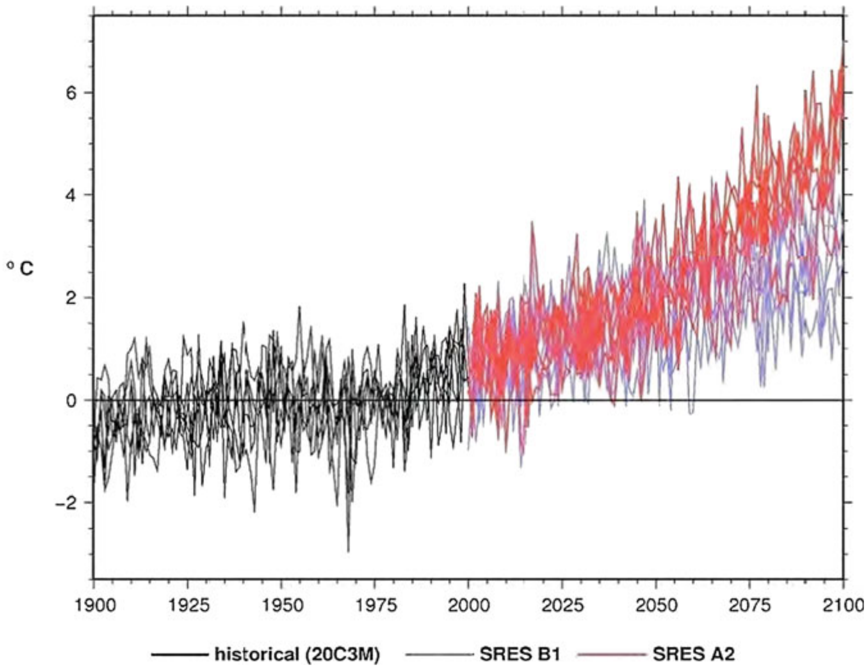

Fig. 17.2 Average annual temperature projections for Sacramento region (departure from 1961 to 1990 historical mean) using six different climate models run under SRES A2 and B1 scenarios (*Source* Cayan et al. 2009)

Projections suggest that compared with the mid-twentieth century average, the Sierra Nevada snowpack may be further reduced by 25–40 % by 2050 (Mote et al. 2005). Loss of northern basins' snowpack, essentially the state's largest surface water reservoir (Madani and Lund 2010), could considerably exacerbate California's water supply challenges.

17.2.3 Precipitation and Runoff

As of 2010, no discernable trend has been observed in California's statewide annual precipitation. Trend lines may indicate a slight increase in precipitation, potentially due to generally dry periods of the 1920s and 1930s. In contrast, California's runoff patterns seem to be changing from recent historical patterns. The state has a seasonal pattern of relatively cool, wet winters and hot, dry summers, typical of the Mediterranean climate. Moreover, temporal and spatial distribution of precipitation in California is markedly uneven. On average, 50 % of the annual precipitation falls in the three months of December, January, and February, and 75 % falls during November through March (Roos 2001; Madani

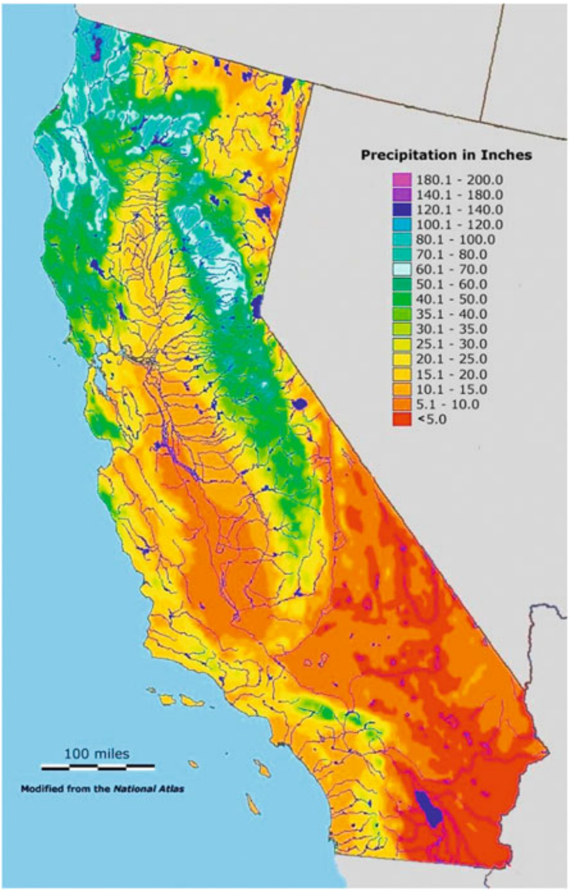

Fig. 17.3 California's water resources including lakes, streams, and reservoirs, along with average annual precipitation (*in inches*) from 1961 to 1990 (*Source* U.S. Geological Survey, http://education.usgs.gov/california/resources.html)

and Lund 2009). Approximately two-thirds of the state's precipitation occurs in the northern one-third of the state (Kahrl et al. 1979). Figure 17.3 shows California's average annual precipitation from 1961 to 1990, along with the state's water resources, including lakes, streams, and reservoirs. The figure illustrates a discernable difference between a fairly dense network of streams in Northern California and the Central Valley, and the infrequent streams in the southern part of the state. Runoff variation in Sacramento Basin is presented in Fig. 17.4. This figure shows the gradually declining trend of April–July runoff as a percentage of total water year runoff. The ongoing trend of climate warming in California may continue to alter spatial and temporal characteristics of precipitation as well as the magnitude and timing of runoff.

The change in California's precipitation amount and form, and subsequent changes in runoff characteristics, are spatially variable. While precipitation in some regions of California has become more abundant, in other regions, particularly Southern California, it has become more scarce. Typically, studies of the

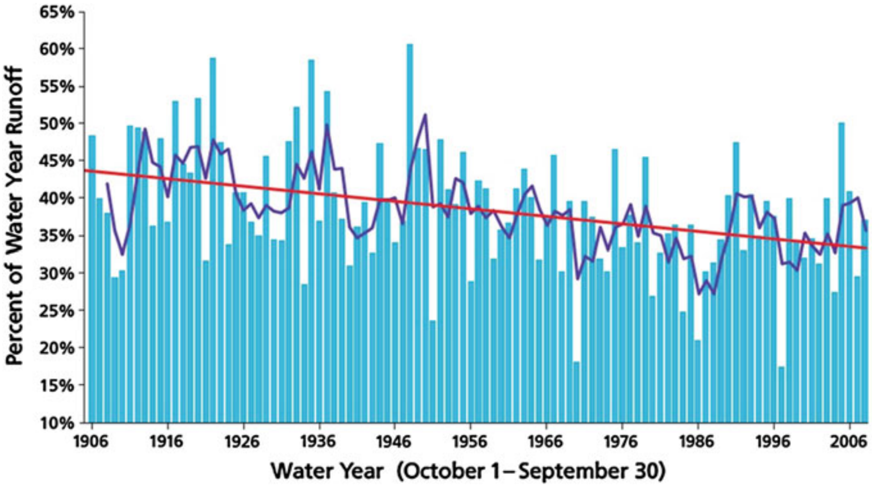

Fig. 17.4 Runoff variation in Sacramento basin; trend of AprilJuly as percent of water year runoff; straight declining line and fluctuating line denote historical trend and three year running average water year runoff, respectively (*Source* CA DWR 2010)

potential impacts of climate change on precipitation have focused on drier outlooks mainly because wetter scenarios are less likely to cause water supply problems. Cayan et al. (2009) demonstrated that results of different climate models, run under different emissions scenarios, are not in complete agreement as to the extent of change in precipitation and runoff processes. They ran six climate models under two climate scenarios (SRES A2 and SRES B1) and found a 12–35 % decrease in mid-century average precipitation. Out of the 12 simulations, only one simulation projected a slightly wetter future, whereas, eleven simulations projected marginally to considerably drier conditions by mid-century. Figure 17.5 presents the projected changes in precipitation in Northern California over the twenty-first century as compared to 1961–1990.

Rising temperatures, especially during winters, will contribute to the gradual precipitation shift from snow to rainfall. Thus, a greater portion of the winter precipitation is expected to occur as rain instead of snowfall, significantly reducing snow accumulation. As a result, the peak runoff from snowmelt and early spring rainfalls is occurring earlier (Roos 1987, 1991; Cayan et al. 2001; Stewart et al. 2004, 2005). Additionally, as the snowmelt period shortens in response to diminishing snowpack in the northern basins, the flow of snow-fed streams in the late spring and summer is expected to decrease (Cayan et al. 2009; CA DWR 2009). Furthermore, more variability in rainfall in the form of wetter winters and drier summers would place severe seasonal stress on water supply systems. A 30 year runoff trend analysis by California Department of Water Resources suggests that the fraction of annual runoff occurring from April through July in the Feather River basin in the northeastern Sierra decreases from about 35 % for the base scenario of historical conditions with no increase in air temperature to about

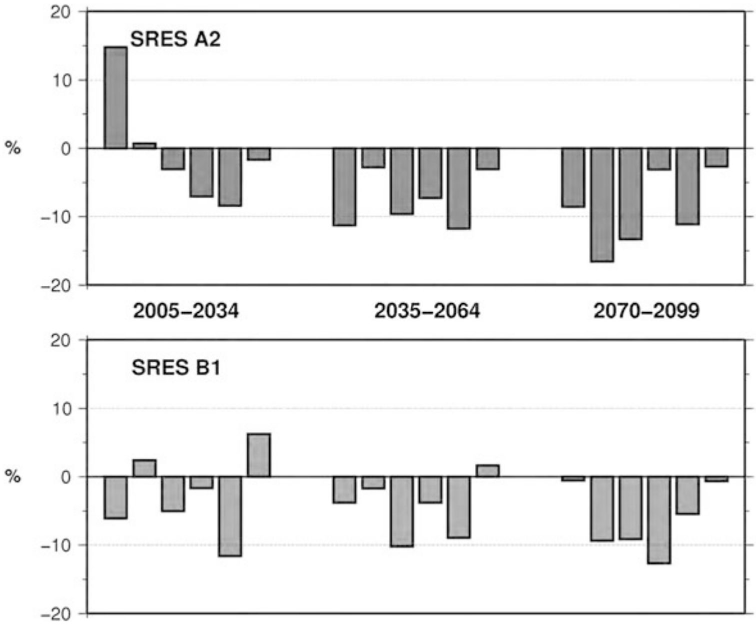

Fig. 17.5 Projected precipitation changes relative to 1961–1990 average precipitation in Sacramento region, using six GCMs (1: CNRM CM3; 2: GFDL CM2.1; 3: MIROC3.2 (med); 4: MPI ECHAMS; 5: NCAR CCSM3; 6: NCAR PCM1) run under *SRES* A2 and *SRES* B1 (*Source* Cayan et al. 2009)

15 % for a +7.2 °F (+4 °C) warming scenario (Chung et al. 2009). It is worth noting that the impact of rising temperatures in the Feather River basin would likely be more significant than in many higher-elevation basins to the south of the Sierra region.

Assuming that no infrastructural changes will be made to the SWP and CVP, Chung et al. (2009) analyzed potential climate change impacts on California's water supply systems. Overall, their results predict a potential water supply deficit in California, due to reductions in Delta exports and reservoirs' carry-over storage. Furthermore, they conclude that as the reliability of the SWP and CVP decreases, a greater share of water supplies will come from groundwater sources. Table 17.3 summarizes the median results for the 12 future climate projections used in their study.

17.2.4 Drought

Drought is a gradually occurring natural phenomenon that can significantly complicate water resources management. Although there are no universal guidelines for identifying the exact start or end time of a drought, a drought may be

Table 17.3 Median results for possible climate change impacts on SWP and CVP using 12 future climate projections based on SRES A2 and SRES B1 (*Source* Chung et al. 2009)

Potential impact	Mid-century: some uncertainty		End of century: more uncertainty	
	SRES A2: higher GHG emissions	SRES B1: lower GHG emissions	SRES A2: higher GHG emissions	SRES B1: lower GHG emissions
Delta exports	−10 %	−7 %	−25 %	−21 %
Reservoir carry-over storage	−19 %	−15 %	−38 %	−33 %
Sacramento Valley groundwater pumping	+9 %	+5 %	+17 %	+13 %
Delta salinity standard (X2)	Expected to be met	Expected to be met	Expected to be met	Expected to be met
System vulnerability to interruption	1 in 6 years	1 in 8 years	1 in 3 years	1 in 4 years
Additional water needed to meet regulations and maintain operations	750 TAF/yr	575 TAF/yr	750 TAF/yr	850 TAF/yr

defined as any extended, abnormally dry period that causes significant hydrologic imbalance. Typical impacts of drought on water supply systems include prolonged below-normal runoff and stream flows, decreasing reservoir storage, declining groundwater tables, and reduced hydropower generation. Hydrologic impacts intensify with the length of a drought, as reservoirs' stored water is used and water levels in aquifers decline (CA DWR 2010).

California's droughts have historically posed difficult challenges on the state's water supply system. There is evidence of severe droughts in California in past centuries (Stine 1994). In the twentieth century, three major droughts (1929–1934, 1976–1977, and 1987–1992) had devastating impacts on California's water supply. The first major drought of the twentieth century in California, with an estimated recurrence interval of approximately 200 years (CA DWR 1976), occurred during the period of 1929–1934. This drought has been widely used as the basis for the design of storage capacity and yield of components of California's water supply system (e.g., many large reservoirs in the SWP and CVP, Northern California). The driest year of California's measured hydrologic record was 1977 with the record low of 15 MAF, causing 47 out of 58 counties in California to declare drought emergency (CA DWR 2010). To put this number in perspective, the average annual runoff in California is about 71 MAF (CA DWR 2000). Figure 17.6 shows how the 1976–1977 drought triggered a shift to using more groundwater in the San Joaquin Valley. The 1987–1992 drought was severe in the San Joaquin region and entailed statewide impacts. Although the state's larger water supply systems (e.g., SWP and CVP) managed to meet delivery requests until the fourth year, declining reservoir storage prompted considerable delivery cutbacks towards the end of the drought period. In 1991, as the drought extended to its fifth year, California's Governor's Drought Action Team appropriated a

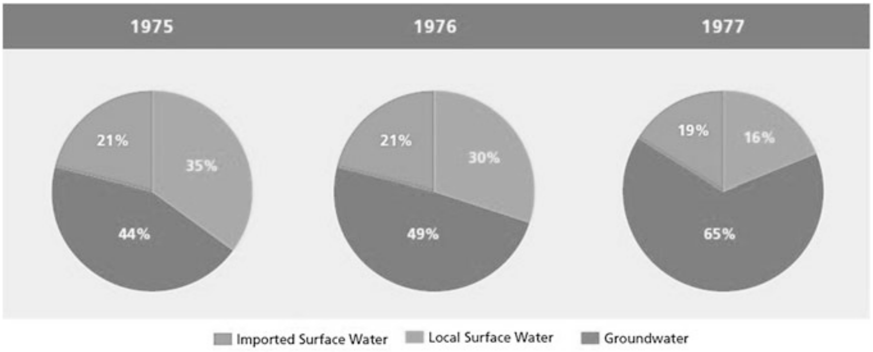

Fig. 17.6 Heightened pressure on groundwater sources in San Joaquin Valley during the drought of 1976–1977 (*Source* CA DWR 2010)

collective sum of $107.4 million to enhance the state's ability to handle drought conditions, and to provide funds for local relief activities (CA DWR 2000). The 2007–2009 drought was California's most recent multi-year drought. Table 17.4 presents a comparison of this drought with major droughts of the past century (CA DWR 2010). Also, Fig. 17.7 illustrates comparison between runoff in an average water year and during droughts in the Sacramento and San Joaquin regions.

There is evidence that droughts will become more frequent and persistent in California in the twenty-first century (e.g., Burke et al. 2006; Favre and Gershunov 2008; Milly et al. 2008). Decreases in precipitation may be sustained by changes in atmospheric circulation that change the mean moisture convergence at the northern edge of the subtropics, including Southern California (Seager et al. 2007). Climate model projections are consistent with evidence that dry spell length has significantly increased in the southwestern United States (Groisman and Knight 2008). Diffenbaugh et al. (2008) found that areas of northwestern Mexico and the southwestern United States, including Southern California, are the most susceptible regions to climate change impacts, mainly due to high rainfall variability. Furthermore, increased temperatures are expected to increase evaporation and transpiration, which will affect soil moisture levels critical to a region's hydrologic balance (Wilkinson et al. 2002). However, the changes in evapotranspiration might not be as significant at higher elevations because the soil in the snow zone will

Table 17.4 Comparison of 2007–2009 with major droughts of the twenty-first century (*Source* DWR 2010)

Drought period	Sacramento river runoff		San Joaquin runoff	
	MAF/y	% average 1901–2009	MAF/yr	% average 1901–2009
1929–1934	9.8	53	3.3	56
1976–1977	6.7	36	1.5	25
1987–1992	10.0	54	2.7	46
2007–2009	11.2	60	3.6	61

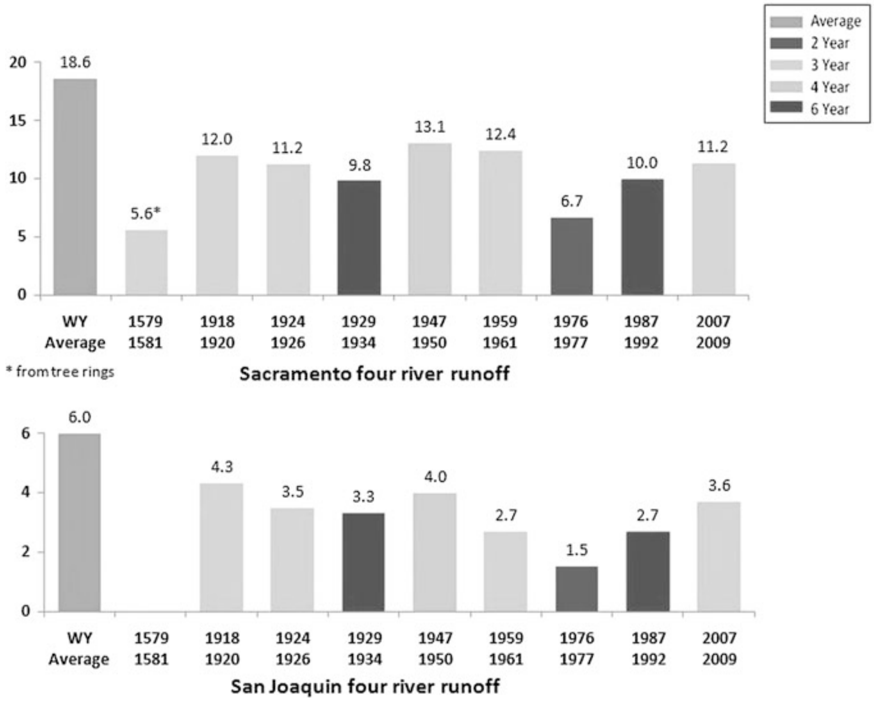

Fig. 17.7 Comparison between runoff in average water year and during major droughts in Sacramento and San Joaquin regions; average annual drought period runoff in million acre-feet (data from the California Department of Water Resources)

likely dry sooner due to earlier loss of snowpack, limiting use by vegetation. Groundwater tables may drop as recharge decreases and agricultural users shift to groundwater sources to cope with droughts. In some parts of California, during droughts, the share of groundwater in the total water supply increases to more than two thirds during drought periods (Fig. 17.6).

17.2.5 Sea Level Rise

Average global sea levels are rising, potentially in response to rising temperatures. Among the factors contributing to sea level change are rising air temperatures, which drive thermal expansion of the ocean, as well as melting of glaciers in areas such as Greenland and Southeastern Alaska (IPCC 2007). Extension of current rates of sea level change into the future results in a 0.5-foot rise by mid-century. Consistent with global trends of sea level change, tidal gauge data at the San Francisco Bay Delta suggest that sea level at this location has been rising during the past decades (CA DWR 2008). Rahmstorf (2007) proposed a methodology for projecting future global sea levels using a correlation between historical surface temperature and historical sea level rise. Other researchers have applied this methodology using projected future surface air temperatures generated by GCM simulations to provide estimates of sea level rise resulting from climate warming (Cayan et al. 2009; Chung et al. 2009). These studies have shown that sea level rise rates will likely be greater than previous estimates (e.g., IPCC 2001). Under SRES A2 and B1 storylines, Chung et al. (2009) estimated a 0.8–1.0-foot rise in sea level by the mid-century and a 1.8–3.1-foot rise by the end of 21st century (Fig. 17.8).

Sea level rise is an important issue for California's coastal water supply systems (e.g., water transfer in Sacramento-San Joaquin Delta). Higher storm and snowmelt runoff in winter coupled with accelerating sea-level rise may result in higher storm surges in the Delta during major Pacific storms. This increases the probability of levee failure and disruption of the conveyance system between northern water supply sources and southern water users. Williams (1987) evaluated the interactions between sea level rise and salt front movement, and potential consequences of failure of levees in the Sacramento-San Joaquin River Delta in Northern California. He suggested that if the levees were to fail, the 1,100-square-kilometer San Francisco Bay estuary could triple in size, causing salinity levels to increase significantly as far as 15 km upstream. Upstream migration of the salt front could adversely affect ecosystems and increase the risk of saltwater contamination at water-supply intakes (Gleick 2000), such as SWP and CVP, the two

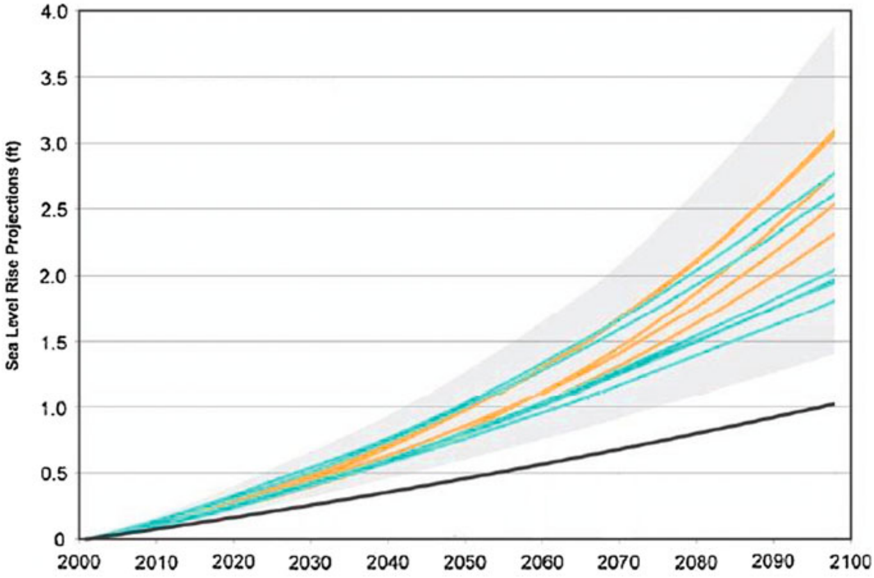

Fig. 17.8 Projected sea level rise using 12 different future surface air temperature projections; *yellow* and *blue lines* denote SRES A2 and SRES B1, respectively; *black line* denotes projection of historical sea level rise; shaded area shows a 95 % confidence interval (*Source* Chung et al. 2009)

major water systems exporting water from the Sacramento-San Joaquin Delta (Wilkinson et al. 2002). Mitigation of the salt front movement may require increased releases from the scarce upstream resources or use of a pumped water transfer system.

17.2.6 Other Impacts

Climate change is likely to alter water quality and the frequency of floods. Pronounced seasonality of runoff due to wetter winters and shorter snowmelt periods may increase the frequency of large floods (Miller et al. 2001; Wilkinson et al. 2002). Potential increase in the number of floods may aggravate water quality problems in California's water supply and adversely affect coastal communities. Changing runoff characteristics, specifically longer low-flow conditions coupled with more frequent and intense storm runoff, could increase nonpoint-source pollution by increasing flushing times and erosion; consequently, water quality in the streams and receiving water bodies, and particularly in coastal wetlands and deltas, will deteriorate (Vaux 1991; Schindler 1997). Thus, climate change will likely affect a range of water quality parameters, including temperature, turbidity, nutrients, toxicity, and salinity.[2]

17.3 Adaptability of California's Water Infrastructure to Climate Change

From a hydrologic perspective, climate warming will potentially exacerbate California's water supply problems. Similarly, water supply sources from outside California (e.g., the Colorado River) are expected to suffer from climate change as well (Gleick and Chalecki 1999). Implications of climate change for California's water supply include reduced water supply from the Sierra snowpack, increased evapotranspiration rates coupled with heightened soil moisture deficits, declining groundwater tables during dry periods, and potential water quality and flooding problems. California depends heavily on runoff from snowpack to provide the water supplies and generate hydropower during the warmer, drier months of the year (e.g., late spring to early fall). Existing water supply infrastructure in California has been designed based on historical hydrologic conditions. With current changes in the form and amount of precipitation, and in the timing and magnitude of snowmelt runoff, California's multi-purpose and single-purpose water infrastructure could face a paradoxical challenge in terms of storing a sufficient amount

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[2] As an example, salinity levels in the San Francisco Bay Delta violated water quality standards in three straight years at the end of 1987–1992 drought (Wilkinson et al. 2002).

of water during the wet season while keeping enough empty space to cope with winter flooding and the risk of uncontrolled spills (Medellín-Azuara et al. 2008; Madani and Lund 2010).

Climate change will likely exacerbate the frequency and magnitude of hydrologic droughts in some parts of California. Enforcement of additional regulatory requirements to protect ecosystems and certain fish species may further reduce water supply for other uses during future droughts. For instance, although the recent 2007–2009 drought was not as severe as past 3 year droughts, its impacts on California's water supply were so significant that a statewide drought emergency was declared for the first time (CNRA 2009). It is expected that climate change will intensify the various use sectors' competition for the over-allocated water supplies in California (CNRA 2009). Furthermore, agricultural water demand is expected to increase as the growing season becomes longer due to higher average temperatures and associated increases in evapotranspiration and soil moisture deficits over much of the year (DWR 2008).

Using the CALVIN (California Value Integrated Network) model under warmer-only and warmer-drier climate change scenarios, Medellín-Azuara et al. (2009) demonstrated that, between 2020 and 2050, California's water supply is expected to decrease by 7 %, and that agricultural water supply will likely decrease by about 15 % (4,070 thousand AF per year [TAF/yr]) due to increased urban demand[3]. This study also found that even with the implementation of water conservation and water efficiency measures, urban water demand is expected to increase by more than 10 % (1,606 TAF/year) between 2020 and 2050, posing additional stress on the decreasing supply (Medellín-Azuara et al. 2009).

While hydropower generation at multi-purpose reservoirs located at low elevations is not affected considerably as a result of flexibility in operations due to high storage capacities (Medellín-Azuara et al. 2008 2009), the high-elevation hydropower system in California may be vulnerable to climatic changes. The high-elevation hydropower system in California holds 30 % of in-state usable reservoir storage capacity and generates about 74 % of in-state hydropower (Madani and Lund 2010). This system is composed of more than 150 hydropower plants located above an elevation of 1,000 feet, and has been designed to take advantage of snowpack, which functions as a natural reservoir (Madani and Lund 2007, 2009). Therefore, snowpack reduction and earlier peak flows may affect the operation of this system. Madani and Lund (2010) evaluated the climate change effects on the high-elevation hydropower system in California, using Energy-Based Hydropower Optimization Model (EBHOM) (Madani and Lund 2009). Their results suggest that California may lose up to 20 % of high-elevation hydropower generation under warm-dry climate change due to a 20 % decrease in annual flows. This loss in generation translates into a loss of revenue of 14 %.

Given the above potential climate change related impacts, it seems prudent to revise and improve California's water resources management strategies to address

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[3] Increased urban demand is expected as a result of population growth.

current and potential future impacts of climate change on California's scarce water supply. To this end, a set of climate change adaptive strategies for water resources planning and management in California has been formulated by the California Natural Resources Agency (CNRA 2009). These strategies focus on a number of areas, including:

- Using sustainable funding sources to develop climate-adaptive, integrated water management plans, emphasizing the conjunctive use of surface and groundwater resources along with water transfer, reclamation, and desalination;
- "Aggressive" increase of water use efficiency and water conservation to achieve a statewide 20 % reduction in per capita urban water use by 2020;
- Adopting a collaborative approach for better decision making, as well as practicing and promoting integrated flood and watershed management inclusive of emergency flood preparedness;
- Sustaining and enhancing ecosystems and habitats in the face of sea level rise;
- Expanding and improving infrastructure such as reservoirs and groundwater storages to accommodate the wet events for flexible management and conjunctive use of surface and subsurface sources; and
- Enhancing Delta water supply as well as its water quality and ecosystem conditions (CNRA 2009).

17.4 Conclusions

Extensive observations and research demonstrate that California's climate is changing. Climate warming has impacted California's water resources by affecting components of hydrologic cycle such as snow accumulation and melt patterns, precipitation, runoff, evapotranspiration, stream flow, groundwater, and receiving water bodies, among others. The mean winter temperature in California's south coast region has increased more than 1 °F (more than 0.5 °C) during the past century. Additionally, although less total runoff is not evident, a trend towards an earlier seasonal streamflow of reduced magnitude has been observed in California's northern basins, most likely due to an increasing trend in temperature levels and gradually diminishing snowpack. Projections suggest that, compared with the mid-twentieth century average, the Sierra Nevada snowpack may be further reduced by 25–40 % by 2050. Likewise, climate models suggest a 12-35 % decrease in average precipitation by mid-century. However, a significant reduction in annual precipitation has not been observed so far.

California's droughts of the last few decades, including 1976–1977, 1987–1992, and 2007–2009, posed difficult challenges for the state's water supply system. As the current trend of climate change continues, its associated hydroclimatic impacts will likely reduce California's water supply by decreasing surface water and groundwater resources, degrading water quality due to increased flooding, and increasing agricultural water demands due to both longer growing seasons and higher evaporation rates. Paradoxically, however, increased urban demands may prompt a decrease in agricultural water use. Moreover, provision of stringent regulations to protect ecosystems and endangered species will increase environmental water demands, further intensifying the impacts of future droughts. California's multi-purpose water infrastructure is already facing critical challenges in terms of meeting supply needs of various use sectors and providing flood protection, and it is likely that climate change will increase the frequency and magnitude of droughts and floods. Furthermore, a potentially accelerating trend of sea level rise could place additional stress on the levee infrastructure in the Delta and threaten intrastate water transfers.

The growing body of evidence for climate warming implies that it is crucially important to revise and improve water resources management to address current and potential future impacts of climate change on California's scarce water supply. Adoption of adaptive management strategies focusing on a collaborative and integrated approach to water resources management seems essential. There is an obvious need for more water storage and more conveyance to balance supply and demand between northern and southern regions in California. In lieu of massive infrastructure investments, more flexible and efficient water resources management schemes involving the conjunctive use of surface and groundwater resources, along with increased conservation and reuse, better emergency flood preparedness, and ecosystem rehabilitation and water quality protection, can help mitigate the impacts of climate change in California.

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Part IV
Economic Considerations and Drought

Chapter 18
Water Scarcity and Droughts in Spain: Impacts and Policy Measures

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Abstract Water scarcity in Spain is driven by substantial irrigation development that took place during last century—first through collective waterworks and more recently by the surge in groundwater pumping. These mounting water scarcity impacts are compounded by quality degradation induced from urban and industrial point pollution, and from agricultural nonpoint pollution. Droughts are a recurrent event in Spain, and the country has progressively developed complex physical and institutional arrangements to cope with droughts—from mild to severe and long-lasting events. But as water scarcity intensifies in nearly all basins, droughts generate higher economic and environmental costs. Environmental effects are especially worrying because adjustments to scarcity and droughts in basins fall mainly on environmental flows, with escalating damages in aquatic ecosystems. While drought measures and plans in Spain have become quite robust and effective in dealing with drought spells, general water policies seem powerless to stop or dampen the worsening water scarcity in basins.

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18.1 Introduction

The pressure on water resources has been mounting worldwide during the last century, creating problems in basins on a global scale, driven by the ever-increasing growth in population and income. The pressures and the resulting damages have been building up rapidly during the last decades, with many basins around the world undergoing pervasive water degradation. The problems created by these growing demands on water resources are twofold. One is water scarcity in watersheds brought about by excessive surface and groundwater withdrawals. The other is water degradation from pollution loads leading to many tracts of rivers and whole aquifers being spoiled, and losing their capacity to sustain ecosystem functioning and human activities.

Water scarcity is created gradually by the decisions on water extractions in river basins linked to land use and economic activities. The problems arising from water scarcity could become critical during drought spells. Droughts are normal and recurrent climate fluctuations that reduce temporary water availability during certain periods, but the natural variability of droughts is being modified by climate change. In some regions, climate change is going to aggravate the severity and duration of drought spells. The combined effects in basins of human-induced permanent water scarcity and very severe temporary drought spells could have devastating impacts. These impacts would affect not only human settlements and their economic activities, but also the natural environment and ecosystems.

Worldwide, the total amount of precipitation is 110,000 km^3, of which 40,000 is runoff and aquifer recharge, and 70,000 constitutes soil storage returning to the atmosphere through evapotranspiration. Anthropogenic water extractions have climbed from 600 to 3,600 km^3 between 1900 and 2000, along with the growth of population from 1.7 to 6.0 billion. Of these extractions, 2,300 km^3 are employed for irrigation, 900 for industrial use and 400 for urban use (FAO-IFAD 2006). Although water returns to basins from these human activities amount to 2,500 km^3, returns contain large pollution loads that degrade heavily water-receiving media.[1]

Water scarcity has become a widespread problem during the last decades in most arid and semiarid regions around the world. There is a severe scarcity problem in almost all the important rivers in these regions, such as in the Nile, Ganges, Indus, Yellow, Yangtze, Tigris, Euphrates, Amu and Syr Daria, Murray-Darling, Colorado and Rio Grande. Surface and subsurface resources are being depleted in these river basins and their quality degraded. The scarcity problems in basins of arid and semiarid regions were created at first by extractions of surface waters, but at present they are compounded by the huge development of

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[1] Return flows are 1,200 km^3 from irrigation, 750 from industry and 330 from urban use.

groundwater by individual wells during the last decades, brought about by the adoption of pumping technologies with falling costs worldwide.[2]

The growing scarcity created by surface and groundwater depletion of basins demonstrates that water resources mismanagement is quite general, and that sustainable management of basins is a complex task very difficult to achieve. The reason behind the pervasive basin mismanagement worldwide is that water is mostly a common pool resource with environmental externalities, and adequate management can only be brought about by cooperation of stakeholders through the right institutional setting (Albiac 2009).

The impacts of droughts on arid and semiarid basins are substantial because they build upon the existing water scarcity situation. This is the case of recent droughts in Australia, the Western United States, China and Africa. Severe droughts could have large impacts on agriculture, domestic and industrial users, tourism, and on the natural environment and ecosystems. Costs of drought damages seem to be considerable, and have been estimated at around 2–6 billion US dollars per year in the United States, and around 3 billion euros per year in the European Union.[3] These costs represent between 0.05 and 0.1 % of the gross domestic product (GDP), although the costs of drought could be exceptionally high some years. Reported losses in Australia during the last drought spell of the 2000s reached 30 % of agricultural output, or 1 % of GDP. However, detailed data on the cost of droughts are not available in most countries.

In Europe, water scarcity and droughts are important and recurrent problems in southern Mediterranean countries. Concerns by these southern countries have been addressed by a Communication on water scarcity and droughts (EC 2007a). However, the fact that droughts and water scarcity deserve only a “Communication” indicates that the European Union gives more importance to flood problems than to water scarcity and droughts. Floods involve mainly northern and central European countries, and a full Directive of Floods has been approved requiring countries to elaborate and enforce flood management plans.[4] Water scarcity and droughts involve mainly southern European countries and the Communication sets up only voluntary drought management plans that are not legally enforceable by the European Union.[5]

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[2] The largest groundwater extractions by country take place in India, the United States and China with extractions above 100 km^3, and in Bangladesh, Pakistan and Iran with extractions above 50 km^3 (Björklund et al. 2009; Vrba and Gun 2004). The region of the Indus, Ganges and Brahmaputra basins is the larger irrigated area in the world, and groundwater overdraft has been estimated at 50 km^3 per year from satellite data (Tiwari et al. 2009).

[3] In the United States, the NOAA (2008) cost estimates are between 1 and 2 billion US dollars per year, and include only crop and property damages, while FEMA (1995) cost estimates range between 6 and 8 billion US dollars per year. In the European Union, the European Commission (2007a) cost estimates are around 3.3 billion euros per year.

[4] Directive 2007/60/EC on the assessment and management of flood risks. The directive requires European countries to assess flood risk and prepare flood management plans.

[5] Directives and communications are quite different policy instruments in the European Union. A directive is legally binding and member countries are responsible for its implementation, with infringements involving large monetary penalties. A communication is a declaration of

The Communication on water scarcity and droughts calls for a drought strategy and a drought observatory at the European level, and the European Commission (2007b) has issued guidelines for elaboration of the voluntary national drought plans. National drought plans are intended to contribute to the implementation of the European Water Framework Directive. The countries with drought management plans already in place are Spain, Portugal, and the United Kingdom. Spain has a long tradition of water planning, and comprehensive drought management plans have already been elaborated and approved by each river basin authority during 2007. In Portugal, the Commission for Reservoir Management is in charge of declaring the presence of drought events based on drought indicators. After this declaration, the drought programs are elaborated and implemented. The United Kingdom established a law related to hosepipe bans, drought permits and drought order works that applies only to England and Wales. The drought plans are prepared in England and Wales by water companies and by the environment agency, and the purpose is to ensure essential public supplies while protecting the environment. At present, the more comprehensive drought plans in the whole European Union seem to be those of Spain.

The issues of water scarcity and water quality, droughts, and severe impacts from the upcoming climate change, are all critical topics in the case of Spain. These issues are discussed in this chapter, which is organized as follows: first a description of responses and adaptations to water scarcity and droughts is presented, then the Ebro basin and the Júcar basin are taken as examples to evaluate policy developments regarding water scarcity and droughts, and finally there is a section with conclusions and recommendations.

18.2 Responses and Adaptations to Water Scarcity and Droughts

Water scarcity and water quality degradation in Spain are the consequence of the growing pressure of economic activities during the last 50 years. Water scarcity is linked to the enormous development of irrigation, while quality degradation is linked mostly to the urban and industrial sectors but also to agriculture. Water extractions for consumptive uses were 15,500 Mm^3 per year in 1960 at the beginning of the industrialization period. Five decades later, these water extractions have doubled up to 32,500 Mm^3, driven by the expansion of irrigation acreage from 1.8 to 3.5 million hectares and the growth in urban and industrial

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(Footnote 5 continued)
intentions, with voluntary recommendations to member countries not enforceable by any regulatory mechanism.

Table 18.1 Water extractions by sector in Spain (Mm^3)

Years	1960	1990	2004
Irrigation	12,800	23,000	25,000
Urban and industrial	2,700	5,800	7,500
Total	15,500	28,800	32,500

Source INE (2009), MIMAM (2000), MOPT (1993)

Fig. 18.1 Basin authorities in Spain

demand (Table 18.1).[6] Urban and industrial uses represent only a fourth of extractions, but their pollution loads are the main causes of water quality degradation and the ensuing environmental damages.

The more acute problems of water scarcity are located in the south and eastern basins, where highly profitable crops such as vegetables and fruits are cultivated under intensive production systems. In other inland Spain basins, irrigated crops are less profitable and are cultivated under more extensive production systems. The problems of water scarcity are linked to the surge in aquifer pumping that occurred in recent decades in the Júcar, Segura, Sur and Guadiana basins, and more recently in the Guadalquivir basin (Fig. 18.1).

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[6] These figures are for consumptive uses, but do not include cooling, hydropower and aquaculture which in 2004 are the following: cooling 6,300 Mm^3, hydropower 50,000 Mm^3 and aquaculture 3,500 Mm^3.

Irrigation in the Júcar basin district expanded from 120,000 to 350,000 ha between 1970 and 1995. Most of the expansion was based on aquifer pumping, which started in the Júcar basin during the 1960s. At present, irrigation demand is 2,550 Mm^3 over a total demand of 3,300 Mm^3, covered with 1,600 Mm^3 of surface and 1,700 Mm^3 of subsurface extractions. Renewable water resources in the basin are around 3,700 Mm^3, which is somewhat above extractions, making the basin district not far from a water closed system. Although renewable resources exceed barely total global extractions, the pressure from extractions is quite large in many watersheds of the Júcar basin district, giving rise to acute scarcity and water quality degradation in locations such as Plana de Castellón, Camp de Morvedre, Safor and Vinalopó.

In the Segura basin, irrigation expanded from 130,000 to 270,000 ha between 1970 and 1995, creating a large pressure on surface and subsurface water resources and a pervasive degradation of river courses and aquifers. Renewable water resources are around 800 Mm^3, supplemented by around 300 Mm^3 of additional external resources through the Tajo-Segura water transfer. These combined resources are well below the current extractions of 1,400 Mm^3, so a large mining of aquifer systems is occurring. In the Sur basin, greenhouse irrigation expanded in Almería from nil to 40,000 ha between 1970 and 2000, resulting in pervasive aquifer overdraft in Campo Dalías and Campo Níjar.

There has been an important mismanagement of groundwater in the upper Guadiana basin in the last 30 years, leading to the disappearance of the "Tablas" aquifer systems and 80 km of the river. The expansion of irrigation started in the 1980s, attaining 150,000 ha in 1990 and 260,000 ha in 2005. The damages on aquatic ecosystems have been large, and involve the Tablas de Daimiel Natural Park, which is the second wetland in importance in the Iberian Peninsula, declared by UNESCO reserve of the biosphere site.

Finally, the more recent uncontrolled expansion of water extractions has occurred in the Guadalquivir basin. The renewable resources in the Guadalquivir basin are estimated at 6,800 Mm^3 per year, and pressures on resources were already high in 1995 with extractions at 3,400 Mm^3 and an already tight allocation between 2,900 Mm^3 for irrigating 480,000 ha, and 500 Mm^3 for urban and industrial demand. In the last 15 years, irrigation has expanded up to 800,000 ha, based of groundwater extractions by farmers that are mostly illegal. The pressure on resources in the basin is growing and water scarcity is becoming acute, especially during dry years.

Current total extractions have escalated to 4,100 Mm^3, of which 3,500 Mm^3 cover irrigation and 600 Mm^3, urban and industrial demand. Groundwater extractions for irrigation have grown from 300 up to 900 Mm^3 in the last 15 years, worsening water scarcity in the basin. The problem is the following: during wet years there are enough resources to cover total irrigation, divided between 2,600 Mm^3 from surface sources and 900 Mm^3 from subsurface sources. However, during dry years, aquifer extractions for irrigation reduce considerably the water contemporary available from surface sources. The result is that rivers run low and only the urban and industrial demand is fully covered because of the

Table 18.2 Fall in precipitation and river flow during the drought of 1991–1995 (%)

Basin	Precipitation	River flow
Duero	16	36
Tajo	21	49
Guadiana	29	74
Guadalquivir	28	72
Sur	23	59
Segura	15	32
Jucar	13	9
Ebro	11	22
All basins	15	28

Source MIMAM (2000)

priority rules, while the deep adjustment falls on irrigation supplied with surface water and on ecological flows sustaining ecosystems.

Surface extractions for irrigation are 2,600 Mm^3, and in dry years these extractions could be reduced by the 600 Mm^3 that aquifer pumping has expanded in the last 15 years. Since total extractions have increased, the pressure on rivers in the basin is worsening the water scarcity problem, and several aquifers are now being overdrafted heavily. The major ecosystem in the basin is Doñana, which is the main wetland in the Iberian Peninsula declared by UNESCO world heritage site. Doñana is seriously threatened by overdraft from irrigation in its surrounding area.

The progressive worsening of water scarcity in most basins in Spain implies that the potential impacts from droughts could be much more damaging in economic and environmental terms. The response of basin authorities to drought spells under these aggravating scarcity conditions has been a more sophisticated and complex elaboration of responses and adaptation measures. Historically, the four more severe drought spells in Spain during the last century have been those of 1942–1945, 1980–1983, 1991–1995 and 2005–2008. The worst drought was the 1991–1995 spell with an average fall of 15 % in precipitation and 28 % in river flows, but with some basins, such as Guadiana and Guadalquivir, sustaining falls around 30 % in precipitation and 70 % in river flows (Table 18.2).

During the beginning of the second half of last century, there was a substantial unbalance between water consumption requirements and available water resources in Spain, aggravated by the strong industrialization process in the country. The drought spells made apparent the need for developing water works. The outcome was a vigorous program of public water works to increase storage capacity and water conveying facilities, which included even inter-basin transfers. The storage capacity of dams between 1960 and 1990 jumped from 10,000 to 50,000 Mm^3.

The three last drought spells of 1980–1983, 1991–1995 and 2005–2008 show similar negative environmental impacts on water depending ecosystems. There was a large decrease in crop production, a massive increase in groundwater drilling, and an alarming fall in the water tables of the main aquifer systems. The overdraft and water salinity impacts were quite obvious in southern and eastern basins, and especially severe in the Júcar, Segura, Sur, Guadiana and Guadalquivir basins.

The drought spell of 1980–1983 reduced substantially hydroelectric generation and created important problems for water supply in many urban centers, especially in southern Spain where even water tankers by truck had to be engaged to supply water to towns and villages. The drought had also effects on land use decisions by farmers, with reductions in dryland cultivation and changes in crop mix. Another effect was that farmers made investments to reduce the risks of not having water, by pushing groundwater drilling and switching to more advanced irrigation technologies such as drip irrigation.

The drought of 1991–1995 caused large economic losses in agricultural activities and hydroelectric generation, but also large impacts in urban and industrial activities. The supply of water for irrigation was banned or halted in the Guadalquivir and Guadiana basins. There were severe restrictions of water supply in the majority of important towns in southern Spain, such as in Sevilla, Malaga, Toledo, Granada, Jaén, Ciudad Real and Cádiz. Urban restrictions included water rationing lasting several months, with no water supplied during 10–12 h per day.

In addition to restrictions and special conditions for trading among users, the more common measures taken were the construction of water conveying facilities among watersheds, the large-scale construction of drought wells by basin authorities, and the use of non-conventional sources. Emergency water-conveying facilities were built to supply Sevilla, Toledo, Jerez, Cádiz and Madrid, and groundwater wells were drilled to supply water to Granada, Madrid, Jaén, Malaga, Santander, Pamplona and other towns. Important well-drilling programs for irrigation were implemented by the Júcar and Segura basin authorities, and thousands of farmers in these basins received special drought emergency drilling permits. The use of non-conventional sources included mixing water resources of different qualities, reutilization of treated wastewater, and supplying water by ship in the cases of Mallorca and Cádiz.

To face the drought impacts, a large number of decrees were passed between 1992 and 1995, creating permanent drought commissions in every basin authority. These commissions were empowered to modify or suspend any water use, compel water users to install measuring and controlling devices in public and private water conveying facilities, and build water extraction and conveying installations under the consideration of emergency waterworks. The approach taken was emergency management without any previous drought planning, and with piecemeal measures decided and implemented by basin authorities as the drought spell lasted longer and its severity became critical. The consequences of this emergency management approach were the following: the drought was detected too late, the measures were improvised on a case by case manner, and the legislative response took time since the first decrees were passed in 1992, two years after the drought started (MIMAM 2000).

The last drought of 2005–2008 was less severe than the previous drought in the 1990s. Urban restrictions did not include water rationing measures, and only irrigation water was curtailed in some watersheds. The drought measures included emergency waterworks in conveying facilities and the recovery of water augmenting facilities built in the previous drought of 1991–1995, such as drought wells and water transport connections among basins. Economic information on the costs of droughts is very scarce in Spain. They usually consist in evaluation of agricultural losses at very local levels by insurance companies or farmers unions. The only reported costs available correspond to the Ebro basin in 2005, with a loss of 20 % of agricultural added value, or 1 % GDP.

During the last drought of 2005–2008, the government asked the basin authorities to prepare the drought plans for every basin. These drought plans were a requirement of the National Hydrological Plan of 2001, and were supposed to be operative by 2003 but, in fact, they were finished and approved in 2007.

The drought plans are based on a global system of hydrological indicators that are used to declare the state of alert or full drought. Each basin authority prepares a drought plan that includes the management rules for watershed systems, and the measures to be implemented in the public hydraulic domain. Public administrations responsible for urban supply systems providing water to more than 20,000 inhabitants are required to elaborate an emergency urban supply plan for droughts. These urban emergency plans have to take into account the rules and measures of the basin drought plan.

The objective of the basin drought plan is to minimize the environmental, economic and social impacts of drought spells. This objective is achieved by guaranteeing water availability to population, avoiding negative effects on the ecological status of water bodies, and avoiding economic losses by following the priority rules of water planning.

The responses and adaptation to water scarcity and droughts in Spain during the last 20 years have been shaped by the national water policies and also by the European Water Framework Directive. The main water policies have been the National Hydrological Plan proposal of 1993, the approved National Hydrological Plan of 2001, the National Irrigation Plan of 2002, the Upper Guadiana Plan of 2008, and the First and Second Sanitation Plans of 1995 and 2008. The European Water Framework Directive was enacted in Spanish legislation in 2003. The directive does not address water scarcity and droughts, which are the main issues in Spain, but rather deals with the water quality of water bodies and the attainment of their good ecological status. However, the Spanish water authorities are going beyond the requirements of the directive by strengthening the minimum ecological flows that existed already in previous basin plans.

The successive National Hydrological Plan proposals of 1993 and 2001 were designed to alleviate the acute degradation of water resources in southeastern Spain, which is in the Júcar, Segura and Sur basins. This degradation was driven by the heavy increase in water demand from the highly profitable fruit and vegetable sectors, including substantial greenhouse acreage. Most of the water demand increase was met by individual farmers pumping from aquifers, which are not controlled by the river basin authorities. Basin authorities perform a good management of surface water, based on collective systems of dams and canals, together with the irrigation water user associations.

Pervasive aquifer depletion in southern and eastern Spain led to the proposal of large water interbasin transfers in both National Hydrological Plans of 1993 and

2001. These large interbasin transfers were met by the opposition of political parties, groups of interest, and donating territories. The ensuing political fight on interbasin transfers has been influencing the results of several state and national elections. Finally, the large interbasin water transfers proposal was cancelled in 2004 and substituted by the so-called AGUA project, which involves large investments in desalination plants to supply the Spanish southeastern coastal fringe with an additional supply of 600 Mm^3 per year.

The investments of water policy planning in Spain are considerable: 19 billion euros for the National Hydrological Plan, 6 billion for the National Irrigation Plan (including the recent Irrigation Crash Plan), 5 billion for the Upper Guadiana Plan, and 20 billion for the Second Sanitation Plan. The National Irrigation Plan and the Second Sanitation Plan seem well designed to improve water quality by reducing pollution loads and, in the case of the Irrigation Plan, have the potential to reduce water extractions (Albiac et al. 2007). But other policies embodied in the Upper Guadiana Plan and the AGUA project of the National Hydrological Plan seem misguided.

The National Irrigation Plan has a good potential for saving water and curbing pollution through investments in advanced irrigation technologies, because technical innovations in irrigation systems facilitate the private and public control of water quantity and quality. The National Irrigation Plan is abating considerably nonpoint pollution loads of nutrients and salinity. However, the potential of the National Irrigation Plan for reducing water extractions will require a strong coordination between water authorities and irrigation water user associations.[7]

The Plan of the Upper Guadiana is an example of an unconvincing water policy being implemented. The plan aims at curbing overdraft in the Western La-Mancha Aquifer and recovering the Tablas de Daimiel natural park, the second main wetland in the country. Previous efforts to reduce illegal abstractions were unsuccessful, and involved large payments to farmers in the 1990s amounting to 250 million euros. Instead of curtailing illegal abstractions, the plan anticipates investments of 5 billion euros to eliminate 180 Mm^3 of overdraft. But the large investments in the Upper Guadiana will not work without carefully designed incentives to gain farmers' cooperation. If the plan approach is generalized to the 500 Mm^3 of aquifer overdraft in the Júcar, Segura and Sur basins, then the additional investments needed would amount to 13 billion euro (Albiac et al. 2009).

The second example of a questionable water policy is the irrigation component of the AGUA project, which is part of the National Hydrological Plan. The AGUA

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[7] An important reason for coordination is the issue of water returns after investing in networks and plot irrigation systems. Water losses in distribution canals and plot irrigation systems return to watersheds, and when water losses are reduced through investments in upgrading networks and irrigation systems, the problem may appear that farmers use the saved water in more water-demanding crops or in expanding irrigation land. The consequence could be an increase in evapotranspiration and the reduction of water flows in watersheds. The solution is reducing water concessions to countervail eventual evapotranspiration increases.

project includes investments of 2 billion euros to build desalination plants and expand supply by 600 Mm^3, of which 300 Mm^3 are for irrigation purposes in the coastal fringe. Although there is a potential irrigation demand in the area from greenhouses and other high-profit crops, pumping costs are much lower than desalination costs, and farmers will not buy desalinated water. Investments in desalination are only justified if basin authorities are able to strictly enforce a ban on aquifer overdraft, forcing farmers to buy desalinated water. But the solution found by the water authorities is subsidizing the costs of desalinated water from around 0.6 euros/m^3 up to the pumping costs of around 0.2 euros/m^3, which are the level farmers are willing to pay.

The National Irrigation Plan, the Upper Guadiana Plan and the AGUA project highlight three different approaches followed by water policies in Spain to solve the worsening water scarcity problem. The National Irrigation Plan focuses on technological innovations, the Guadiana Plan focuses on payments to farmers in order to buy their eventual extractions cutbacks, and the AGUA project involves large-scale investments in seawater desalination to augment water supply.

With respect to droughts, the drought plans required by National Hydrological Plan of 2001 have been prepared and approved in each basin. They are now ready to be applied and include urban emergency plans for towns above 20,000 inhabitants, which is the more critical component of water demand to be covered during drought events. The costs and scale of drought measures would depend on the future overall water scarcity outlook in basins, because drought measures would become more complex and costly as basins become more and more water scarce. Given that water scarcity has been augmenting in almost all river basins in Spain during the last decades, the question then is the following: are water policies in Spain going to stop or dampen down the progressing water scarcity in basins? The answer is important in environmental and economic terms, because as river basins become closed, both water resources degradation and damages on ecosystems escalate considerably, and current and further development of economic activities is threatened.

18.3 Case Studies: The Ebro and the Júcar Basins

The responses to water scarcity and adaptation to droughts are very different in the Ebro basin and in the Júcar basin, because of their fairly diverse physical and economic conditions. The Ebro basin district covers a fifth of the Spanish territory, and the Ebro River gives its name to the Iberian Peninsula. It is the longer river with the larger flowing stream in the country. Although there is substantial irrigation acreage in the basin, the pressure on water resources from population and economic activities is less severe than in southern and eastern Spain. The river flow at the mouth has been falling in recent decades, but the river is not closed, as is the case in other basins. However, the new water plan draft of the Ebro basin indicates that the limit of extractions has been reached in most watersheds, and these ceilings are especially tight in the basin right hand tributaries (CHE 2009).

The Ebro basin renewable resources are estimated at 13,900 Mm^3, and these resources sustain 8,150 Mm^3 of water extractions, of which 7,800 Mm^3 come from surface sources and only 350 Mm^3 from aquifers. The main use of water is agricultural production with 7,340 Mm^3 employed to irrigate 800,000 ha. Urban demand is 350 Mm^3, serving a population of nearly 3 million inhabitants, and including domestic demand and network connected industries and services. Direct extractions by industries amount to 220 Mm^3, and there are also non-consumptive extractions for cooling (3,100 Mm^3) and hydropower (38,000 Mm^3).[8]

The fraction of consumptive extractions per year over renewable resources is 60 %, and further pressure from economic activities has to be curtailed to avoid the gradual closing of the basin. The current water extractions are already bringing about noncompliance with the minimum ecological flow thresholds for some rivers and periods established in the basin plan of 1998. Noncompliance is occurring in between 10 and 30 % of the stations measuring water flows (CHE 2008). The Gállego and Guadalope tributaries located in the middle Ebro basin, show a very high frequency of noncompliance flow events. The Ebro river flow in Zaragoza (middle Ebro) and Tortosa (mouth) show some significant noncompliance flow events. The basin river flows have been quite stable during the last decade, but implementation of the Water Framework Directive involves higher minimum flow thresholds in order to achieve the "good" ecological status of water bodies.

Some measures have been taken to curtail water extractions in the aquifers with the more serious overdraft problems, such as the Alfamen, Campo de Cariñena and Campo de Belchite aquifers. There are temporary limitations to additional extractions in these aquifers and in some other aquifers in surrounding locations, by stopping the issuance of new extraction permits. New programs are being prepared to improve flow measurements and to verify concession licenses in the rivers Aragón, Gállego, Cinca, Segre, Noguera-Pallaresa, and along the Ebro to fulfill the new monthly flow regimes.

The forthcoming Ebro basin plan 2010–2015 has not been approved yet, and the planned investments have been downscaled from 10 to 5 billion euros. The main investment components are 2.5 billions for irrigation, 0.5 billions for wastewater treatment plants, and 0.5 billion for dams and water conveying facilities.

The Ebro drought plan was approved in 2007 and it is going to be part of the new Ebro basin plan. It includes the system of indicators, the drought management rules for the watershed boards, and the urban emergency plans. There are progressively stringent drought measures for the whole basin when the drought situation goes from pre-alert to alert and emergency. There are also specific measures for each watershed, which are taken by the watershed boards. Under alert and emergency drought situations, the permanent drought committee is established.

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[8] There are 180 Mm^3 of interbasin transfers to País Vasco and Cataluña supplying urban and industrial uses.

The drought measures include questions such as priority of water uses and demands, water-use restrictions, ecological-flow regimes when urban uses are threatened, operating rules for interconnecting conveying facilities linking different water sources or watershed boards, launching existing drought-purpose facilities (water transfers, drought wells, river pumps).

The Júcar basin district covers almost a tenth of the Spanish territory in the eastern part of the country. The basin district has an irregular Mediterranean hydrology, and the main rivers in the district are the Júcar, Turia and Mijares Rivers. The name of the basin comes from the Arabic word "xuquer," which means "destroyer," because of the Júcar River's historical devastating floods (CHJ 2004). Droughts and flood events are quite common, and the rising pressures from human activities on water resources in the last decades have turned the basin district in an almost hydrologically closed system. The very intensive and profitable agricultural production, coupled with high population density and extensive economic activities, have generated serious water scarcity and water quality problems in most rivers and aquifers of the basin. The main water scarcity problems are located in Plana de Castellón, Camp de Morvedre, Safor and Vinalopó.

The Júcar basin district renewable resources are 3,700 Mm^3, and these resources sustain 3,300 Mm^3 of water extractions for consumptive uses (irrigation, urban and industrial). The balance between resources and extractions is quite tight, and does not leave too much water for the natural environment supporting the water-depending ecosystems. This stringent balance means that the rivers in the district are becoming progressively closed, with some aquifer systems being overdrafted. Surface water extractions amount to 1,600 Mm^3, but the use of subsurface water is substantial and growing. Aquifer extractions were already 1,500 Mm^3 in 1990, and they have expanded to the current 1,700 Mm^3 volume. The main water use is agriculture production with 2,550 Mm^3 to irrigate 352,000 ha. Urban supply is 630 Mm^3, of which 550 Mm^3 covers the domestic demand of 5 million inhabitants, and 80 Mm^3 covers network connected industries. Direct extractions by industries amount to 105 Mm^3, and there are also non-consumptive extractions for hydropower and cooling (CHJ 2009).[9]

The fraction of consumptive extractions per year over renewable resources is 90 % and, therefore, the basin district is becoming closed. The aquifers in the basin district with the more severe overdraft problems are Plana de Vinaroz (25 Mm^3 overdraft), Plana de Castellón (70) in the Mijares River, Plana de Sagunto (30) in the Palencia River, Mancha Oriental (80) in the upper Júcar, and Jumilla-Villena (35) and Villena-Benejama (40) in the Vinalopó River. Water quality in aquifers is quite degraded, especially in the coastal fringe with nitrate concentrations above 50 mg/l and conductivity measurements above 2.0 dS/m.

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[9] Surface water sources supply 1,300 Mm^3 for irrigation, 220 for domestic demand, and 80 for industries connected to urban networks. Subsurface water sources supply 1,270 Mm^3 for irrigation, 330 for domestic demand, and 100 for industries with direct extractions.

The lower Júcar River undergoes severe problems of low flows and water quality degradation. Average flows are around 5 m^3/s in the Sueca weir and below 5 m^3/s in the Cullera weir. There are high levels of pollutants, with nitrate loads above 20 mg/l and very low concentrations of dissolved oxygen.

There are new provisional minimum flow thresholds for the rivers Júcar, Turia, Mijares, Palancia and Serpis that will be enforced in the forthcoming Júcar basin hydrological plan. These minimum flows are larger than the previous minimum flows established in the Júcar basin plan of 1998, but no information is available on the fulfillment of these minimum flows since 1998.[10] There are also provisional restrictions on subsurface extractions to protect aquifers, which will be enforced in the new Jucar basin plan.

The more important aquatic ecosystem in the Júcar basin is L'Albufera wetland, which is a natural park on the coast. L'Albufera receives water from the returns of the irrigated district fed by the Acequia Real canal. The problem is that both the Acequia Real canal and the irrigation systems in the parcels of the district are being updated with large public and private investments. The outcome is that irrigation returns to L'Albufera are falling,[11] and its ecosystems are being threatened. The basin authority is analyzing the measures to be taken to protect L'Albufera.

Droughts are frequent events in the Júcar basin district, threatening irrigation and urban supplies but also aquatic ecosystems. The main effects are the reduction of water flows and the worsening of water quality. The water table falls in aquifers because of reduced recharges and increased pumping. Drought events complicate the management of streams, reservoirs and aquifers in the Júcar basin, because many stakeholders are not represented in the dam commissions in charge of water allocation decisions.

The last 30 years have been very dry in the basin, and climate change is going to increase the frequency, intensity and duration droughts in it. The decade 1991–2001 was very dry, and during the period 1992–1996 the fall in water flow was 45 % in the Turia River and 35 % in the Júcar River. As a consequence, the Júcar River tract in the Mancha plain along the Eastern La Mancha aquifer was dry during the summers of 1994 and 1995.

The last drought of 2004–2008 was the more severe drought spell of the last 50 years in the Júcar basin district. The year 2005–2006 was the driest year in the Júcar River ever and one of the driest in the Turia River. During this drought, the Júcar River was almost totally dry in Cuasiermes, where the river runs along the Eastern La Mancha aquifer.

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[10] For example, the minimum flow at the Magro station in lower Júcar was 0.2 m^3/s in the Júcar basin plan of 1998, and this flow is going to be increased to 0.2–0.3 m^3/s in the forthcoming plan.

[11] See Albiac et al. (2007) for an explanation of why investments in irrigation modernization usually reduce stream flows.

18.4 Conclusions and recommendations

Water scarcity is becoming a serious problem in most basins in Spain, a country in which droughts are a recurrent event. Basin authorities in Spain have implemented quite sophisticated measures and arrangements to cope with droughts. However, water scarcity in nearly all basins is growing and seems unstoppable, with drought spells generating higher economic and environmental costs. Environmental damages are escalating because the adjustments to scarcity and droughts fall mainly on reduced environmental flows with a degraded water quality.

Water scarcity is a gradual process of rising water extractions in basins becoming closed, with extractions driven by decisions on land use and economic activities. The water scarcity problem is widespread in most arid and semiarid regions around the world, with a quite general mismanagement of water resources. Because water is mostly a common pool resource, a more sustainable management of water resources entails measures to induce the collective action of stakeholders under the right institutional setting.

In the arid and semiarid regions of Europe such as Spain, the management of water scarcity and droughts is an essential component of water policies. The European Union has addressed water scarcity and drought problems by issuing a Communication with voluntary commitments and not fully legal enforceable obligations as in the case of the Floods Directive. This fact seems to indicate that water scarcity and droughts have a low-priority level in European water policies.

The Communication calls for a drought strategy, a drought observatory and voluntary national drought plans. The only countries with some kind of drought management plans are Spain, Portugal and the United Kingdom, although only Spain has comprehensive drought plans with detailed preventive and remediation measures for every basin and sector in the economy.

The growing pressures of economic activities in Spain during the last 50 years are responsible for the impending water scarcity and water-quality degradation. Water extractions have doubled since the beginning of the industrialization period in 1960, in parallel with the surge of point and nonpoint pollution loads. The more acute water scarcity and quality problems are located in southern and eastern Spain basins, driven by the surge in aquifer pumping that occurred in recent decades in the Júcar, Segura, Sur and Guadiana basin districts, and more recently in the Guadalquivir basin. The worst situation is that of the Segura basin, which is a closed water basin with extractions surpassing by far the renewable resources, followed by the Júcar basin district in which the proportion of extractions to renewable resources is 90 %.

The worst drought in Spain took place from 1991 to 1995 with several basins sustaining 70 % reductions in river flows. There were severe restrictions of water supply in most southern Spain towns, including cuts of service half days, lasting several months. The more common measures taken were restricting or cutting supply, construction of emergency water conveying facilities, large-scale drilling of drought wells, and the use of non-conventional sources by mixing resources of different quality or reusing wastewater.

Drought plans have been elaborated in Spain for each basin district and approved in 2007. They are based on a system of indicators, drought management rules for watershed boards in every basin district, and urban management plans. A permanent drought committee coordinates the progressive stringent measures, which are general for the whole basin or specific for watershed boards.

During recent decades, the policy measures to deal with water scarcity and droughts have been shaped by the main national water plans: the National Hydrological Plan, the National Irrigation Plan, the Upper Guadiana Plan, and the First and Second Sanitation Plans—all with multibillion budgets ranging from 5 to 20 billion euros. These plans address the severe degradation of water resources occurring in southern and eastern basin districts, but they show varying degrees of success or failure. The National Irrigation Plan seems well designed to abate pollution loads and has the potential to reduce water extractions. But other policies such as the Upper Guadiana Plan and the AGUA project of the National Hydrological Plan seem misguided.

The Ebro and the Jucar basins are two important basins in Spain with fairly sophisticated water management authorities, and they have been analyzed as case studies of responses to water scarcity and droughts. The responses are different among basins, given the diverse physical, economic and institutional conditions. One important difference is that the proportion of extractions over renewable resources is 60 % in the Ebro and 90 % in the Júcar, showing that the Júcar basin district is almost a closed basin. Neither the National Irrigation Plan nor the AGUA project of the National Hydrological Plan seem able to impede the Júcar basin becoming fully closed. The ongoing construction of the Júcar-Vinalopó water transfer will further expand water extractions from the Júcar River by 80 Mm^3. This development gives the impression that Spanish society and policy makers prioritize expansion of water supply over protection of water resources and aquatic ecosystems.

The cases of the Ebro and Júcar basin districts show that drought management measures are easier to implement in the Ebro than in the Júcar. The reason is that water supply in the Ebro comes from surface sources, which are collectively managed by the basin authority. However, in the Júcar, half of water supply comes from subsurface sources. When drought spells occur, the dam committees and the watershed boards in the Ebro district are able to respond with quick and effective measures. But in the Júcar district dam committees and watershed boards could deal only with surface water, leaving aquifer pumping out of control.

The drought plans of basin districts are now ready to be applied, and include emergency plans for towns, which are the critical issue in drought events. The costs and scale of drought measures depends on the water scarcity outlook in basins, with closed water basins requiring the more complex and costly measures. The key question for water policy makers in Spain is the following: are water policies going to be able to stop or dampen down the progressive scarcity in river basins? The answer will determine if river basins become closed with escalating degradation of water resources and damages to ecosystems, but also creating more difficult conditions for human activities.

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Chapter 19
Modeling Economic-Engineering Responses to Drought: The California Case

Josué Medellín-Azuara, Richard E. Howitt and Jay R. Lund

Abstract Recurring droughts pose predictable challenges to water resources management in California. Disparities in water demand and supply over both space and time, fast-growing cities, prominent agriculture, and increasing concerns on maintaining and improving habitat for native species are among the most salient challenges to water allocation in the state. This chapter explores portfolio approaches to water management under drought conditions. We analyze water management portfolios that are economically optimized to minimize water scarcity and operating costs within some physical and operating constraints. Water management portfolios include intra- and inter-regional water transfers, flexible water storage operations, and conjunctive use, water conservation, and water augmentation via reuse or desalination. This enables us to identify economically attractive opportunities for re-operation of the water supply system. Results from the case studies indicate that despite the significant reductions in water supply under drought or climate change, California's inter-tied network of water resources has the ability to adapt in the long term to these drought events by adding operational flexibility in the system.

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19.1 Introduction

Several authors have defined drought using dimensions such as duration, magnitude and severity (Dracup et al. 1980; Wilhite and Wood 1985). Drought definitions also vary by location and field of study. Hydrologists may be concerned with streamflows, meteorologists with precipitation, agronomists with soil moisture and yields, and economists with sector output. In general, drought is related to a water deficit on a particular time scale and a region in reference to a particular supply and demand (Dracup et al. 1980). Indeed, the definition of drought is fundamental in the characterization of its nature. There can be seasonal droughts, over-year droughts, and prolonged droughts.

In some parts of the world, such as the humid eastern United States, droughts can be as short as a few weeks to a few months, with most damages from effects on rain-fed agriculture. In the western United States and other Mediterranean climates, seasonal hydrologic droughts, which are far more severe than those experienced in the eastern United States, are an annual occurrence, often with almost no precipitation for 6 months of the year. Superimposed on these seasonal droughts are multi-year droughts, which in some places of the arid southwestern United States may last up to six years. Less frequent are multi-decade droughts, which have been known to last for more than a century (Stine 1990).

Climate change also has a role in characterizing droughts. Winters with less water demand coupled with less precipitation stored as snow may result in earlier peak streamflows for most locations. Depending on the form of climate change, drier warm seasons may reduce overall water availability, calling for longer term adaptation strategies in water management.

Each age adapts to the climate and water conditions of its time and place, taking advantage of the economic conditions and societal demands of the time. We view a drought as the divergence of expectations and preparations for water use from the realized supply quantity due to unanticipated hydrologic conditions.

The chapter opens with a review of California water history and droughts from 1905 to 2003. We then show how recent drought impacts and adaptation options can be measured by an economic-engineering model. Both agricultural and urban impacts are discussed. In the third section of the chapter, the integrated CALVIN model of the California water system is used to suggest large-scale adaptations to drought conditions.

19.2 California Droughts

Water supply and demand in California generally do not overlap in space or time (Figs. 19.1 and 19.2). The northern part of the state has most of the surface water availability from winter precipitation and spring snowmelt. A Mediterranean climate and multi-year droughts pose additional challenges to water resource

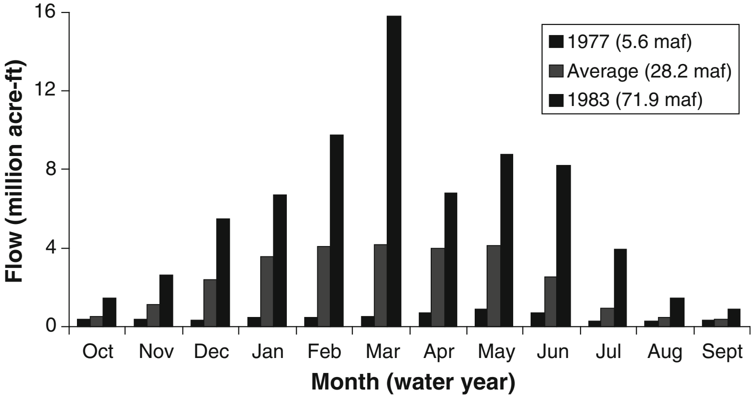

Fig. 19.1 Seasonal and inter-annual flow variability for unimpaired Sacramento—San Joaquin Delta outflows, 1922–2003. *Source* DWR (2007)

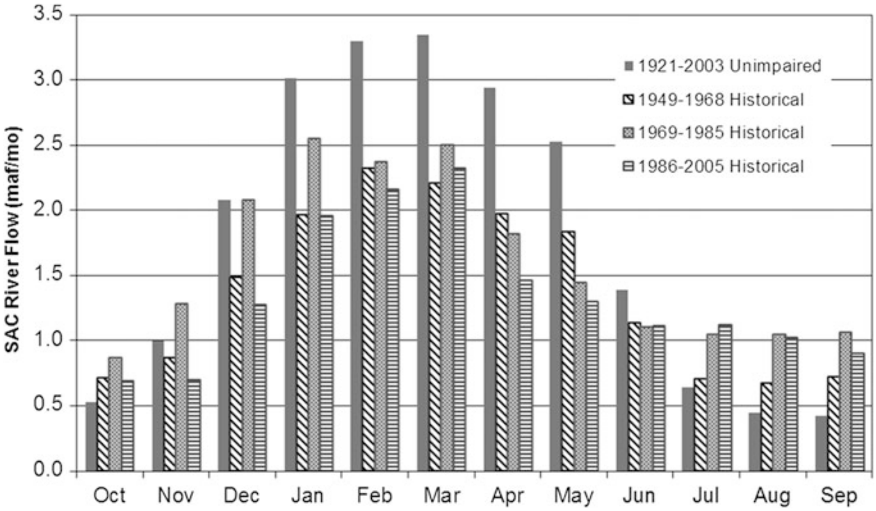

Fig. 19.2 Changes over time to monthly average Sacramento Valley outflows (maf/mo) compared to the unimpaired record during the water year (October–September)

management in this region whose economic wealth depends on water. Water allocation is a challenge for major water projects and hundreds of local water districts and agencies across the state.

Figure 19.3 shows the Sacramento River outflows from 1905 to 2003 with respect to unimpaired flow conditions, before man-made diversions, impoundments, and other alterations to the natural flow regime. A decline in Sacramento-San Joaquin Delta outflows is more evident between 1986 and 2005 for the winter

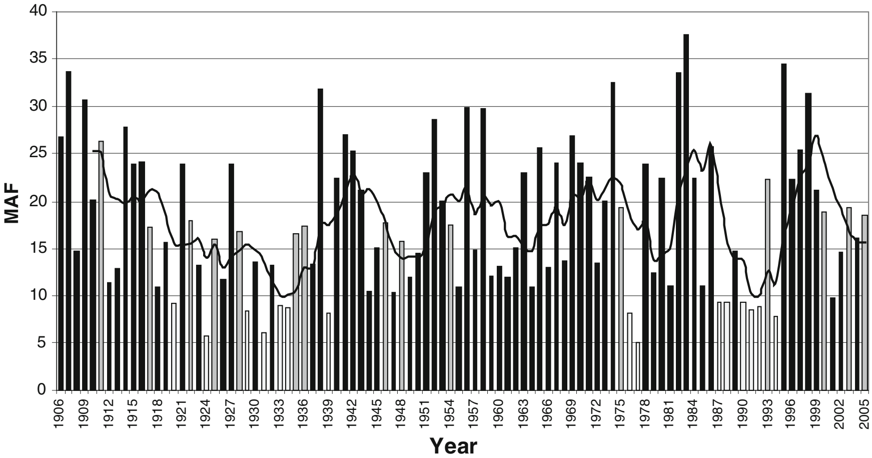

Fig. 19.3 Annual variability in Sacramento River outflow, 1905–2003. *Source* DWR (2007)

and spring (December–May) by comparing the red striped (historical) and solid green (1921–2003 unimpaired) bars in Fig. 19.2.

Water systems in Mediterranean climates must be designed with drought management as their central aim. Drought response can be divided into short-term drought response efforts and long-term drought preparation activities.

Three categories of infrastructure influence drought response: First is the physical infrastructure, which takes the form of surface and groundwater storage, and supply connections that facilitate transfers. Second is the biological infrastructure in which biological assets can be made more or less drought resilient. With the rising social valuation of the environment, the resilience of biological assets to drought is a critical constraint on the adaptability of supplies to drought conditions. Finally, what we call the social response infrastructure reflects the willingness of society or policy makers to modify water demand and supply under drought conditions. Demand modifications are often encouraged by price signals, or social persuasion, either of which can lead to changes in individual water use (Renwick and Green 2000). Supply modifications generally take the form of groundwater overdraft, shifting water from agriculture to other uses through crop fallowing and water trading.

The analysis of drought response can take place at the household, regional, and statewide level. A common thread is the need to integrate the hydrologic, economic, and biological uses of water and restrictions on the system. We use a hydro-economic analysis of drought in California as an example of integrated response methods.

19.3 Assessing Drought Impacts and Adaptation Options with Economic-Engineering Models

To evaluate the potential physical and economic impacts of future drought and water scarcity in California, a number of integrated economic-engineering models, often referred to as hydro-economic models, have been developed. In this chapter, these models have been used to evaluate: (1) the agricultural production response to extreme-drought events; (2) the urban sector least-cost adaptation strategies with portfolio approaches in both California and Amman; and (3) the irrigation impacts and adaptation strategies, including opportunities to reduce overall impact through water transfers amongst irrigators, and between the irrigation and urban sectors.

Key themes that emerge from this review are the use of optimized portfolio analysis approaches to identify economically promising and robust strategies, the substantial opportunities to reduce impacts of drought with water trading or markets, and the importance of conjunctive use of ground and surface waters to draw down groundwater during drought, followed by refilling in wet periods. The greatest research and policy challenges are institutional; namely, coordinating the operation of a complex and highly decentralized system under stressful conditions. Water markets are found to provide improved incentives under these circumstances.

19.4 Agricultural Response to Drought

We use economic engineering models to demonstrate how the physical and financial impact of droughts on the urban and rural economy can be measured, and how such models can be used for policy planning. Between 1998 and 2005, California agriculture, on average, used more than 33 million acre-feet annually in applied water to irrigate 9.2 million acres (DWR 2009). Agricultural revenues in the order of $22 billion in crop farming (USDA 2007) yielded an average of $667 dollars per acre-foot of applied water. Research suggests reductions in system-wide scarcity and operating costs of supplying water can be achieved with more water transfers from low-value to high-value agriculture, and when transfers from agriculture to urban uses are allowed (e.g., Draper et al. 2003; Pulido et al. 2004). Allowing more flexible operations in Southern California, including transfers from low-value to high-value agriculture and urban uses, is estimated to reduce the operating costs of supplying water by $1.93 billion (2008) at 2020 level of development.

The use of water markets is widely advocated as a mechanism to alleviate the economic impact of droughts. Water market implementation, however, is not exempt from challenges in California. During the 1991–1994 California drought, a state-sponsored emergency drought water bank played a significant role in establishing the value of water and reducing the economic costs of major shortages. Most of the effect was concentrated in urban areas, but some high-value agriculture also benefited. Under the most recent 2009 drought, an attempt to repeat this emergency bank was not met with success, given water trades were largely blocked by environmental activists and local interests in exporting regions. This shows that institutional constraints, coupled with private interest and environmental concerns may not provide (at least in the current political and regulatory climate) a venue for an efficient drought water market in California.

To provide an illustration of the potential usefulness of hydrologic-economic models as well as the potential benefits of a portfolio approach to water management that includes water markets, consider the following analysis of the impacts of drought on mostly agricultural activities within the Central Valley. Having most of the water availability in the northern part of the state, the Sacramento-San Joaquin Delta (the Delta) serves as the natural hub for the California intertied water system. The Delta outflows in the San Francisco Bay and hosts pumping facilities that pour water from the Sacramento and San Joaquin Rivers into the two main conveyance systems south of the Delta: The Delta-Mendota Canal and the California Aqueduct. These facilities carry more than 6 million acre-feet per year of water for agricultural and urban uses to supply the rather surface-water-dry Central Valley floor south of the Delta, and the highly urbanized areas of the southern coastal region of the state, including the Los Angeles metropolitan area.

Dry or critical years in California and environmental streamflow requirements that protect native fish habitat pose significant challenges to California's major water projects in their efforts to deliver water to local agencies and farmers. The 2009 drought in California is an example of how these two external events can severely impact water availability. Howitt et al. (2009a, b) use a systems approach to quantify the economic impact of reductions in contract water deliveries south of the Delta. Revenue losses in agriculture are connected to a statewide input/output multiplier model (IMPLAN) that serves to estimate direct, indirect, and induced effects of changes in the crop farming sector on the rest of the regional economy.

Howitt et al. (2009a, b) adapt the Statewide Agricultural Production Model (SWAP, http://swap.ucdavis.edu; Howitt et al. 2012) to include constraints that limit the amount of crop stress. These take the form of restrictions that ensure that applied water cannot be less than 85 % of the base year applied water rate. Increases in groundwater pumping are restricted based on past maximum drought pumping levels, particularly in regions on the west side of the Central Valley where a decline with respect to 2000 levels has been noticed. The effect of drought conditions on crop prices is modeled by endogenous prices, in which the resulting price of the crop group is a function of the quantity produced and the projected, in-state and out-of-state crop demands. A 90 % exceedence scenario for water deliveries is examined in which only 10 % of the Central Valley Project (CVP) contract water is delivered south of the Sacramento-San Joaquin Delta, and 15 % in the northern section in the Tehama-Colusa region of the Sacramento Valley. Under these circumstances, only 40 % of the state water project (the second largest project in the state) is delivered. Nevertheless, senior water rights, settlements and exchanges are supplied at 100 %. In lieu of these water cutbacks, agricultural revenue losses totaling $710 million (2008) can be expected; additional groundwater pumping will add $147 million in system-wide operating costs. Under these scenarios, job losses of around 21,000 are incurred due to water cutbacks and mandated flows to protect fish in the Delta (Howitt et al. 2009a).

Adaptation to drought in California and restrictions on water movement through the Delta provides a strong incentive for water users south of the Delta to explore opportunities for inter-regional water trades. Agriculture, the largest user of water, has the potential to trade the largest volumes, even though institutional constraints for inter-regional transfers exist. Using existing major water infrastructure and information within SWAP (Howitt et al. 2012), feasible and economically justified trades can be calculated. To avoid the adverse reaction to water trades that move water out of county economies, we set institutional constraints for this transfer that restrict water trade to within-county trades, and also restrict the quantity traded from any location to 5 % of the total use in any sector.

Figure 19.4 shows trading regions classified as exporters and importers. Potential amounts of traded water among regions are calculated for an idealized water market (e.g., zero transaction costs), given water-trading restrictions by quantity, type, and location. Furthermore, transport costs based on the distance between trading regions are taken into account. Table 19.1 shows the potential transfers among regions in acre-feet (AF) per year. A pattern for trade can be seen in Fig. 19.5, where water regions east of the Central Valley (in green) are net exporters of water and regions west (in orange) are net importers of water presumably due to higher-value crops and limited water supply.

At the start of the 2009 drought, California water bank operators reported a demand for 44 and 824 Total Acre-Feet TAF/year in the north and south regions,

Fig. 19.4 Agricultural regions south of the Delta

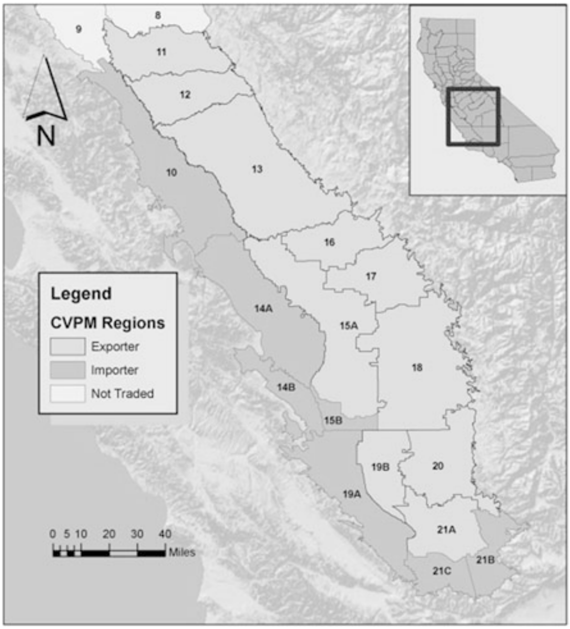

Table 19.1 South of Delta economically optimal water trades (AF/year) adapted from Howitt et al. (2012)

		V11	V12	V13	V14B	V15A	V17	V21A	Import total
Import regions	V10	0	0	0	0	0	0	0	0
	V14A	52,318	37,155	80,599	3,614	34,576	20,350	0	228,612
	V15B	0	0	0	0	0	16,644	0	16,644
	V19A	0	0	0	0	55,825	0	11,104	66,929
	V20	0	0	0	0	0	0	0	0
	V21B	0	0	0	0	0	0	13,049	13,049
	V21C	0	0	0	0	0	0	0	0
	Export total	52,318	37,155	80,599	3,614	90,402	36,994	24,153	325,235

respectively. By the end of the water season in October, water transfers within the northern valley region exceeded the projected demand by 100 % and were almost 89 TAF. In sharp contrast, largely due to real and contrived environmental restrictions, exports from the north to south of the Delta were approximately 200 TAF during this water year, only satisfying 25 % of the projected supply shortfall and resulting in substantial crop, revenue, and employment losses.

In a retrospective analysis of the 2009 drought, several impacts were less severe than anticipated. The most striking finding was that despite some restrictions, more than 500,000 acre-feet of water transfers took place in 2009, which served to significantly offset some of the localized effects of the drought. Additionally, local surface water supplies were higher than last expected, due to late-season rains. The combined effect resulted in an 11 % cut in total average water supply, about half of the best-available estimate in September 2009. As a result of the better-than-anticipated water supply, revenue losses, fallowed acres, and job losses were lower than previously forecast. Revenue losses were estimated to be $370 million with approximately 270,000 acres fallowed. The corresponding agricultural job losses were estimated to be 7,500.

19.5 Large-Scale System Management for Drought

California adapts and reacts to drought at local, regional, and statewide scales. CALVIN, a hydro-economic model for water resources in California (http://cee.engr.ucdavis.edu/CALVIN; Draper et al. 2003) allows statewide integration of water management over time (Fig. 19.6). CALVIN applies economic-engineering optimization to elicit least-cost water allocation and worthwhile infrastructure expansions either regionally (Newlin et al. 2002; Pulido-Velazquez et al. 2004; Tanaka and Lund 2003) or statewide. Hydrology in CALVIN can consider historical (1921–1993) conditions or one or more forms of climate change (Tanaka et al. 2006; Medellin-Azuara et al. 2008; Connell et al. 2012) at different levels of

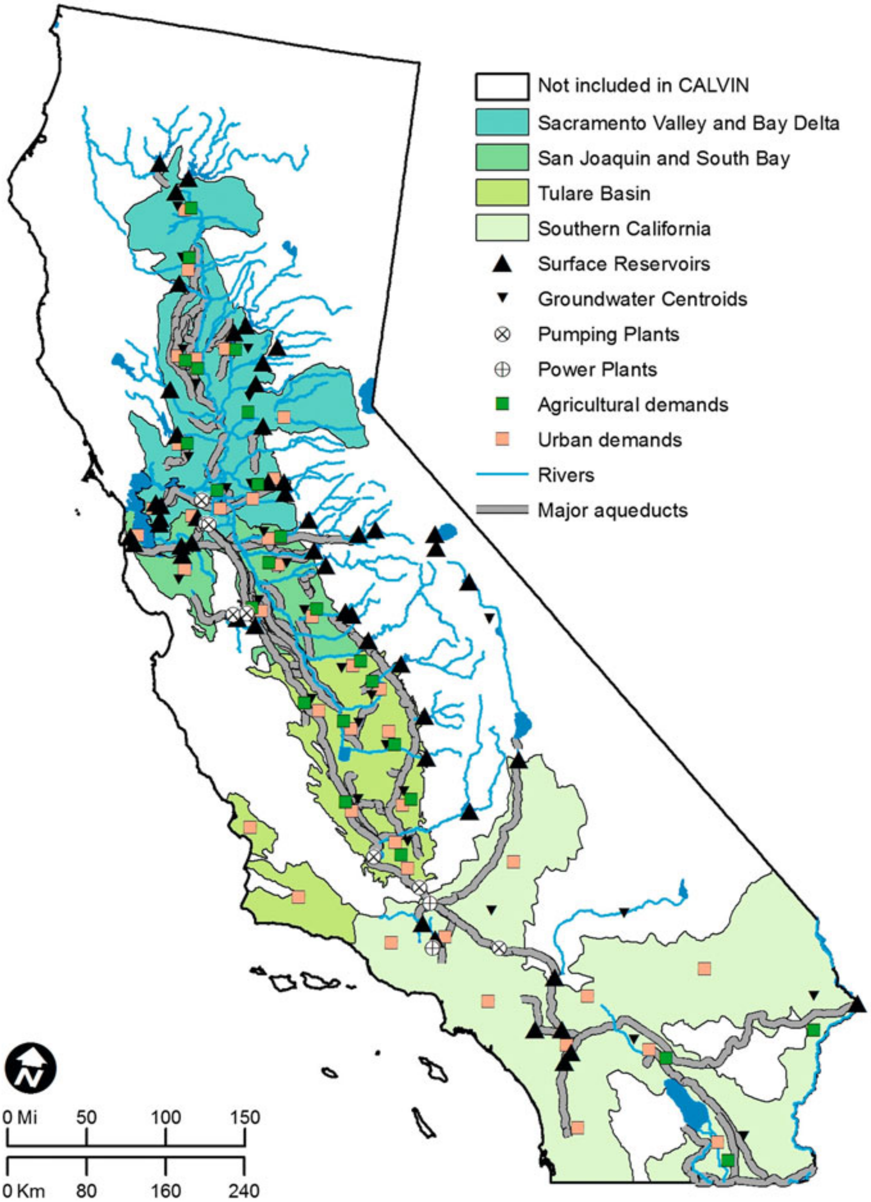

Fig. 19.5 CALVIN, a hydro-economic model for water resources in California (Adapted from Draper et al. 2003)

development for urban, agricultural, and environmental water needs. CALVIN is a network flow optimization model that includes nodes, links, sinks, and sources. Links in the model in most cases represent physical connections that carry water

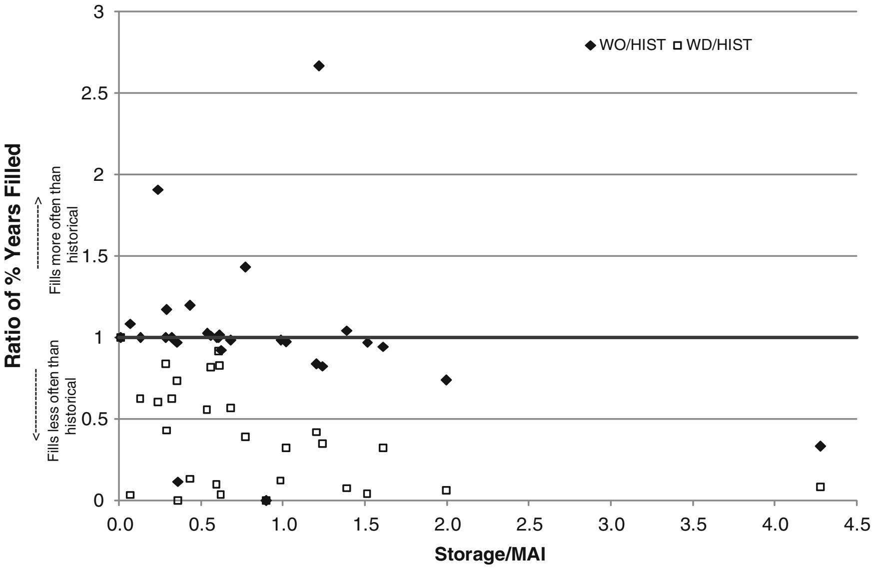

Fig. 19.6 Ratio of percent of years filled versus storage-MAI (mean annual flow) ratio for select surface water reservoirs, comparing both warm-only (dark diamond) and a warm-dry (white square) forms of climate change to historical hydrologic conditions. Adapted from Connell et al. (2012)

between nodes. Nodes are mostly reservoirs, water-demand areas, pumping, hydropower, or simply connecting points. Links may have associated costs that represent either operating costs such as pumping or scarcity costs from shorting water to a demand area. The water scarcity cost in CALVIN at the economically optimal levels of water allocation represents the total willingness to pay for demand fulfillment if enough water were available for either farm production or urban water uses. Some links may include hydropower benefits (which are operationalized as negative costs).

The water supply network in CALVIN (Fig. 19.5) includes major aqueducts, surface and groundwater reservoirs, pumping stations, hydropower facilities and more than 88 % of the currently irrigated agriculture and populated area statewide. The system is programmed to minimize total scarcity and operating costs of the system over a 72-year (1921–1993) time period. This 72-year hydrology is obtained from externally calibrated simulation models, including the Central Valley Groundwater and Surface Water Model (CVGSM) and the Department of Water Resources Simulation Model (DWRSIM) for surface water (Draper et al. 2003).

In this section, we present two recent drought applications of CALVIN—one is under a warm-dry climate change scenario, and another is under an extreme paleo-drought. Despite the severe water deficits, California's inter-tied water system is shown to have enormous potential to adapt to these droughts by optimizing water allocation, and storage and conveyance, with water markets and conjunctive use operations among other economically worthwhile water management strategies.

Warm-dry or warm-only forms of climate change may show their presence in California's hydrographs in the decades to come. Past paleodrought events may recur in a geological time-scale (Harou et al. 2010; Connell et al. 2012). Hydro-economic models allow spatial representation of water resources, infrastructure, management options, and economic values in a region (Harou et al. 2009). Within this framework, it is possible to derive an economically optimal water resources management portfolio for a region. Connell et al. compared the effects of two forms of climate change. A warm-dry climate change represented by 27 % less precipitation, a 28 % reduction in surface runoff to the CALVIN modeling area, a 37 % increase in evaporation, and a 10 % reduction in groundwater inflows. The warm-only climate change hydrology is one in which historical mean annual flows are maintained, while the weight under the annual distribution of runoff for the warmer-only climate is shifted more towards the winter and early spring. Connell et al. (2012) concluded that a warm-dry climate change scenario will stress water allocation significantly more than a warm-only form of climate change. They also concluded that additional storage capacity under the dry climate conditions might not add significant benefits for water management flexibility, as reservoirs are less likely to be filled due to reduced mean annual flows.

According to classical reservoir design and operations theory (Hazen 1914), having over-year storage capability in reservoirs ameliorates impacts from seasonal flow changes. Figure 19.8 shows the relative frequency of filling as a percentage of years filled, versus the ratio of storage capacity to mean annual inflow. The percent age of years filled is generally less for reservoirs under a warm-dry climate; hence, reservoirs fill more often with warm-only conditions. Therefore, the nature of climate change, whether warmer and drier or just drier, greatly influences whether additional storage relieves water scarcity and adds beneficial flexibility to the system, or goes unused if the reservoirs rarely fill.

Geological evidence suggests that during the past few thousand years, century-long droughts have occurred in California, with reductions in annual rim flows ranging from 40 to 60 % (Harou et al. 2010). Under such conditions, trade, water operations, and water rationing are needed to allocate water among those beneficial uses with the highest scarcity costs, within a system of natural, infrastructure, and institutional constraints. Although adaptation requires tradeoffs in water allocation, surprisingly the economic consequences are not catastrophic.

For instance, a base case alone with constrained operations under historical hydrology is likely to yield scarcity costs of $1.59 billion by year 2020. A historical hydrology under more flexible water allocation schemes results in $123 million in scarcity costs. The paleo-drought hydrology with flexible operations would raise the statewide scarcity costs to $1.68 billion, slightly more than the base case. In the base case, scarcity cost is concentrated in urban uses ($1.56 billion), while in the flexible operation scheme with a paleo-drought scarcity costs are concentrated in agricultural uses ($1.04 billion). This highlights the potential of more flexible water allocation schemes as an adaptation to drought.

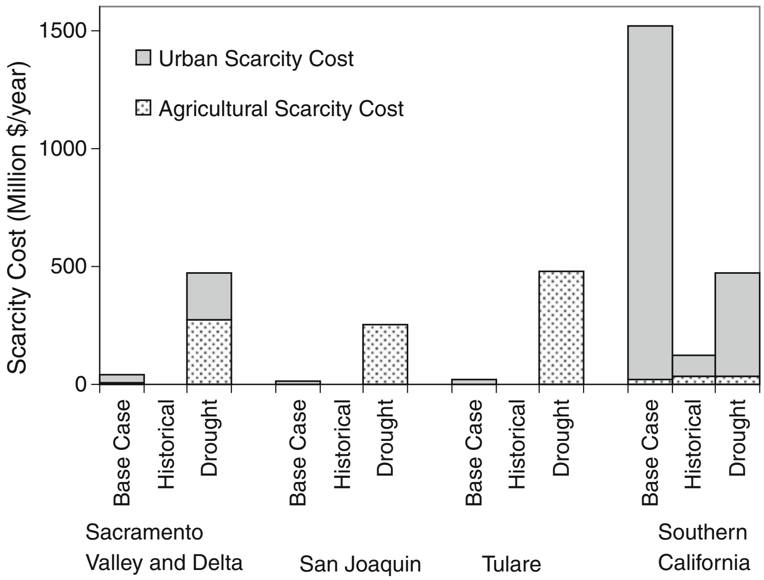

Fig. 19.7 Scarcity costs under the base case, historical and drought conditions (Harou et al. 2010)

Under economically optimal water allocation conditions, agricultural water use and some mandated environmental inflows shoulder most of the burden in the system when streamflows are severely reduced. A 47 % reduction in rimflows in California's Central Valley translates into scarcity costs of up to 10 times the cost of the system managed under a scheme of flexible water operations with historic hydrology. Furthermore, if we assume base case conditions, with institutionally constrained operations, scarcity costs are higher than in a flexible operations scheme with historic hydrology (Fig. 19.7). Costs for the case in which current system operations evolve incrementally towards a more flexible water allocation scheme lie between the drought and base case. However, even under extreme drought conditions, scarcity costs are lower than under the base case scenario in regions such as Southern California. This result highlights the potential of more flexible operations to cope with water scarcity in the system. Surface and groundwater storage operations also adapt to help manage scarcity in the system.

19.6 Limitations and Future Directions

Water management, assuming idealized minimum cost operating conditions, allows the water planner to identify economically promising solutions to water supply problems. Some of these solutions may face challenges in their implementation. In California, physical and institutional constraints for transferring water between regions, a complex structure of water rights, groundwater basin adjudication, and other factors limit promising allocations and operations in some regions. Nevertheless, a quantitative analysis of these water issues is useful to improve understanding of the system and nudge the policy process towards more economically efficient solutions. However, economic incentives and judicial processes alone are not sufficient. Stronger institutions with significant stakeholder involvement often will be necessary.

While the main empirical examples of this chapter have focused on drought and agriculture, urban water issues are certainly important. Urban water demand response to drought is complex to model and entails many potential water management strategies involving a range from a few people at household-scale decisions, to millions of households for decisions at a regional scale. Quantitative representation of such problems and solutions are needed to make sense of such complex problems. In this section, we examine the roles of analytical methods for integrated water resources management for developing portfolios of optimized water management activities, including both short-term drought response efforts and long-term drought preparation activities. Several applications are presented for urban water utilities, household water management, and regional and statewide scale perspectives on drought problems.

Arbues et al. (2003) conducted an extensive survey of the methods and challenges facing the estimation of urban water demand and its price response relative to the model specification, dataset, and other econometric issues. Among these estimation issues, endogeneity due to block-rate pricing schedules creates the greatest concern. Creative ways of overcoming this issue have been demonstrated in the literature since Taylor (1975) and Nordin (1976). As a result, statistical methods dominate the literature on urban water demand. Results from most studies

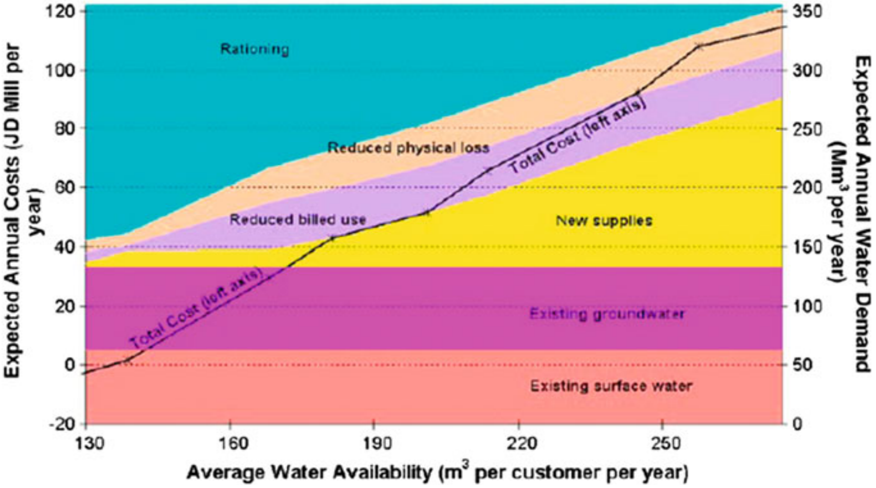

Fig. 19.8 Costs of increasing water availability to water customers in Amman (adapted from Rosenberg and Lund 2009)

show that the demand response to prices is inelastic. Water demand is shown to be more elastic in the summer months, when more flexibility in water use is possible. However, most statistical studies do not address water supply reliability and consumer willingness to pay for water. The importance of reliability as a supply property is noted by several authors, and it can be analyzed using optimization methods (Alcubilla and Lund 2006). Such studies can identify household strategies to manage water scarcity.

Future directions in exploring residential water use response to drought should, when possible, use an integrated bottom-up approach that includes household, utility, and regional planning water management actions. For a better understanding of water management in Amman, Jordan, Rosenberg and Lund (2009) modeled long- and short-term strategies to increase water supply reliability for a municipal water utility. Using stochastic optimization, portfolios of actions were identified to help the municipal utility cope with shortages. They found that large infrastructure investment and exorbitant operating costs in activities such as seawater desalination could be postponed in this dry region (Fig. 19.8). Instead, water conservation via leakage repairs, customer education, water conserving appliances and rebates at the household level would, collectively, decrease water shortages sufficiently. This is illustrated in Fig. 19.8 above. The first two lower boxes in the figure show existing sources that can meet about 135 Mm^3/year (109.5 TAF/year) in total demand. However, annual costs nearly double (left axis) as availability per customer increases (horizontal axis), from base 200–260 m^3 (0.16 to 0.21 TAF) per capita, per day. Physical water losses in the system and unbilled ones are significant in the system and take part of the gains from new sources. Water supply reliability can also be achieved by adopting low-cost brackish water desalination in the longer term.

19.7 Conclusions

The analysis of economically optimal drought response requires the formal integration of hydrologic and behavioral models, since both functions interact and both will be changed under drought conditions. The variation in water demands between drought and non-drought periods at a given price is generally larger than the demand variation under the full range of water prices and average water conditions.

Water management under drought requires a quantitative understanding of the regional water resources system. Tradeoffs of specific water management policies can be identified and quantified using the systems approach of hydro-economic optimization models. Hydro-economic optimization models have the potential to provide policy insights and economically efficient opportunities to allocate, store, and convey water in space and time for alternative water management portfolios and institutional constraints.

The examples in this chapter show that for urban and agricultural water users, the ability to adjust water use and technology on several margins is essential to reducing the hydrologic and economic impacts of droughts.

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Chapter 20
Principles for Economically Efficient and Environmentally Sustainable Water Markets: The Australian Experience

Jeffery D. Connor and David Kaczan

Abstract With growing water demand for cities and irrigation, periods of low inflow increasingly lead to "operative" droughts when supply is insufficient to meet all consumptive and environmental water demands. This chapter focuses on water markets as a mechanism for sharing scarce water in drought. The institutional arrangements in the Australian Murray Darling Basin (MDB) that have allowed emergence of what is arguably the world's most active water market are outlined. The evidence, consistent with economic theory, confirming significant economic benefits from water trade during the recent Murray Darling Basin drought is presented. The yet unresolved challenges arising from increased efficiency of water use in response to water market incentives eroding environmental flow are discussed. The conclusions outline institutional design principles from Australian experience for realizing efficiency benefits and avoiding adverse environmental impacts when introducing water trade.

20.1 Introduction

With growing population and wealth, come growing rates of water diversion for municipal, industrial and irrigation uses, often at the expense of water-dependent ecological assets. When increasing diversions collide with periods of low inflow, the result is often what Pulido-Velazquez et al. (2006) refer to as "operative" drought: a period when supply is insufficient to meet all consumptive and

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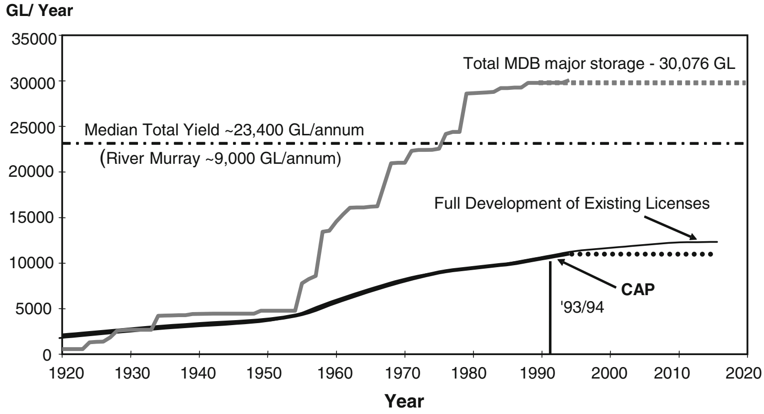

Fig. 20.1 Historic water diversion trends in the Murray Darling Basin

environmental water demands. Climate change predictions for increasing frequency and intensity of such low inflow periods in many of the world's arid and semi-arid basins (Ragaab and Prudholm 2002) are likely to increase the frequency of such operative droughts.

The Australian Murray Darling Basin (MDB) recently experienced an operative drought. Levels of water diversion in the MDB grew over the later half of the twentieth century as shown in Fig. 20.1. As a result, over the period 1990–2006, 56 % of MDB flow was diverted for consumptive uses on average (CSIRO 2008). The second half of the twentieth century, when diversions were growing, was a relatively high-inflow period compared to the first half of the century (Fig. 20.2). A notable feature of this period of growing water allocation was less inter-annual inflow variability than in the periods preceding and prior. As Fig. 20.2 shows, three protracted multiple-year dry periods have occurred over the last 117 years in the MDB—two in the first half of the twentieth century and one from 2000 to

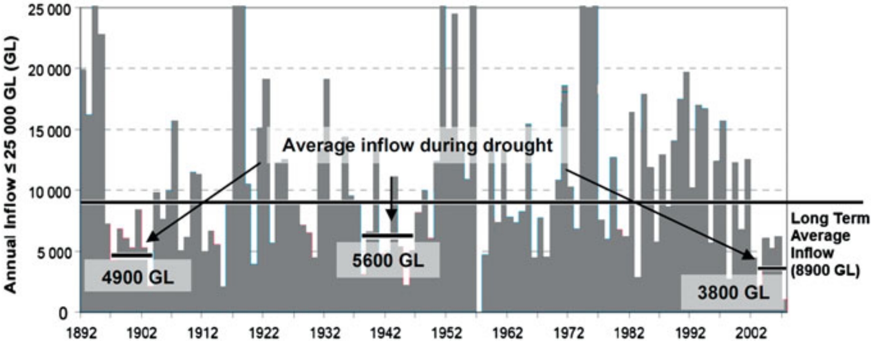

Fig. 20.2 Historical inflows and periods of multiple year drought in the Murray Darling Basin

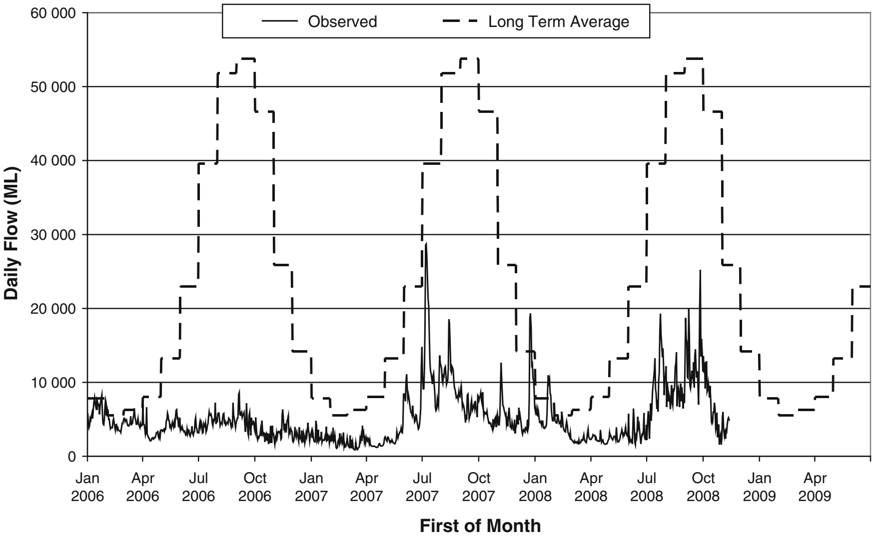

Fig. 20.3 2006 to 2009 Murray Darling Basin inflows

2010. Notably, all three droughts fell outside of the wet second half of the twentieth century when allocations grew.

As shown in Fig. 20.3, the years 2006–2009 represent an unprecedented set of consecutive years of very-low inflows. The result is the most severe operative drought on record, with water available for irrigation diversions at about 25 % of the previous 114-year average in 2008–2009. Results include threats to viability of the water supply from the Murray to the city of Adelaide, with a population of 1.3 million (see Maier et al. 2013 for more detail), and deterioration of the condition of key ecological assets dependent on environmental flow (see Overton and Doody 2013 for more detail).

The introduction of water policy reforms in the 1990s leading to volumetric, metered, and tradable water rights led to the evolution of efficient water markets in the southern part of the basin.[1] This created an opportunity to re-allocate water from low- to high-value uses in the recent drought and thus reduce the overall economic impact. In this chapter: (1) the Australian institutional context that has led to what is now arguably the world's most active water market is described; (2) the evidence regarding the extent to which this economic instrument has reduced the adverse economic impacts of current operative drought is synthesized; (3) the

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[1] In the northern part of the system, consisting of the Darling its tributaries and the Lachlan, a northern tributary to the Murray, little trade takes place. As inflows are extremely variable, water is captured in on-farm dams, with allowable diversions a function of flow, as opposed to a volumetric water right. With this allocation system, if an upstream party trades water downstream, water rights holders between the two could divert flows intended for the downstream party.

yet unresolved challenges arising from increased efficiency of water use in response to water market incentives eroding environmental flow is discussed.

The essence of the unresolved challenge in Australia, and indeed anywhere that water markets are introduced, is a classic dilemma in the water trade literature: (a) define water rights to protect third parties but with high transaction costs that limit potential benefits of water trades, or (b) choose a simpler definition that facilitates low transaction costs with less concern for third-party water rights. The conclusions outline institutional design principles from the Australian experience that might go some distance toward resolving this dilemma and allow for both realizing efficiency benefits and avoiding adverse environmental impacts when introducing water trade.

20.2 Water Trade as an Institutional Approach to Sharing Water in Drought

In many basins, the sharing of water is governed by administrative rules dictating who receives how much, depending on overall supply. In the Western United States, for example, sharing is typically by the prior appropriations doctrine. This system, often referred to as a "first in time, first in right," involves attaching a date of issue to each right to take water from a dam. Water is then released to rights holders in the order of the seniority of rights issued. In times of scarcity, when there is insufficient water to satisfy all claims, water is released to rights holders in the order of the water rights issue dates. In times of scarcity, senior water rights holders receive all of their water right, while junior rights holders receive less than their full allocation.

Australia also has administrative rules for sharing water in times of scarcity. Each water rights holder is issued with water access entitlements, defined as "a perpetual or ongoing entitlement to exclusive access to a share of water from a specified consumptive pool as defined in the relevant water plan" (NWC 2008). Then in any given year, depending on resource availability, all water access entitlement holders are issued water allocations, defined as "specific volumes of water allocated to water access entitlements in a given season, defined according to rules established in the relevant water plan." Allocation levels are expressed as a percentage of entitlements. This percentage varies by year with allocations; a lesser percentage of entitlements in drought and a greater percentage in years of plentiful water availability.

A number of water-sharing plans exist within larger basins, such as the MDB, with separate plans for areas delineated by major catchment and state boundaries. The water released to rights holders as seasonal allocations under rules defined in plans varies across plans with water rights. In some plans, rights to a more reliable supply are referred to as high-security entitlements, while rights to a less reliable (more variable) supply are referred to as general security entitlement. The reliability of water rights "pools" in this system vary with the degree of inflow variability and the degrees of conservatism with respect to leaving reserves in dams to mitigate against potential risk of future low-inflow years. For example, New South Wales plans tend to release a greater proportion of water held in dams in a given year, while Victorian plans tend to hold more water over as contingency for protracted drought.

Administrative rules specifying water-sharing arrangements, including how reductions in water availability are shared among rights-holders, represent a fundamental underpinning of any effective definition of water property rights. However, such approaches often fail to allocate water efficiently to highest-value uses without complementary institutional arrangements. What is needed as a complement are arrangements to allow for flexible re-allocation of water among rights holders, depending not only on the evolution of scarcity but also the evolution of technology, prices, and preferences.

One approach to allowing flexible adaptive changes in how water is shared involves negotiated arrangements among water rights holders and parties with stakes in the outcomes of water-sharing arrangements. The basin water resource planning approach implemented in the Júcair Basin in Spain exemplifies how such an approach can work effectively. In the Júcair basin during a recent operative drought, water flows to a significant wetland were enhanced through reductions in river water diversion for irrigation negotiated in a deal involving compensation for reduced supply and source substitution from river flow to recycled water. Albiac et al. (2013) suggest that the success of this approach can best be realized through a well-documented and broadly accepted common understanding of basin water resources, their interdependence, and multiple-use values. A challenge with this approach is that rather substantial technical and stakeholder engagement efforts are required. Another challenge, reflected in the Spanish experience, is that often the only effective way to claw back water in drought involves expensive compensation (Albiac et al. 2013).

Allowing water to be traded is another way to introduce flexibility and adaptive capacity into water property rights systems. Economists suggest that developing capacity to allow low-transaction costs trades among water rights holders should allow flexible and continuous water reallocation as market conditions, social preferences, and technology evolve. The approach has the potential to allow a set of decentralized individual water rights holders to reallocate water in ways that increase social benefit. The informational advantage of a market is that it tends to lead to efficient social outcomes through individual water rights holders acting on specialized individual information about the productive value of water in their enterprise (Vaux and Howitt 1984).

However, as noted by authors such as Easter and Dinar (1999), realizing the full potential of water trade as a mechanism to efficiently re-allocate water would require:

- Fully defined, monitored and tradable volumetric water rights;
- Low transaction costs market places (e.g., eBay-type Web trading facilities) for annual allocation and permanent entitlement trade, including fast and secure transaction clearance processes;

- Opportunity for environmental water holders representing public environmental, municipal, industrial, and irrigation interests to fully participate in markets;
- Mechanisms to protect against strategic manipulation of market power;
- Mechanisms to calculate and appropriately prorate volumes of tradable water, based on return flow and evaporation impacts of trades;
- Mechanisms to calculate and introduce accountability for third-party water quantity and quality impacts of trades.

Despite the decades of economists' rhetoric advocating water markets, the reality in most basins to date has been quite limited water trade. In the United States, where the preponderance of economic arguments for such markets arises, relatively little trade has actually taken place. Some trade takes place among irrigators within districts with the Colorado Big Thompson district being a widely discussed example. Several examples of environmental trusts exist related to buying irrigated farms and retiring water rights in environmentally strategic regions such as headwaters where returning flows can enhance fish breeding (Landry 1998). In California offers have been made to temporarily lease water from farmers in years of drought (Howitt 1994). Yet highly active water markets similar to purchase and rental markets for real estate are not a reality in most of the United States, nor is there reporting of highly active water markets elsewhere internationally.

20.3 Institutional Set-Up for Murray Darling Basin Water Trade

An important antecedent to water trade in the MDB was a major process of microeconomic reform in Australia over the past 20 years, in particular the Water Reform Agenda of 1994. This included establishing a National Competition Council with a Water Reform Agenda. The agenda has many similar goals to the now widely discussed European Union Water Framework Directive. Goals include full cost-recovery pricing, elimination of cross-subsidies, and separation of water resource management from service provision. The Water Reform Agenda involved establishing water plans for water resources throughout the MDB. As noted above, these water plans defined water entitlements—perpetual rights to a share of a consumptive pool defined in a water plan, and water allocations, annually varying water volumes granted to entitlement holder in a specific season, defined according to rules established in the relevant water plan.

One of the most significant water policy reforms that gave rise to widespread water trade was separation of water property rights from land. Previously, many irrigation property rights were a right to water access associated with land ownership. In some cases, this involved a right to use water attached to a land title but without a volumetric water right. In other instances, an annually variable allocation per hectare of land with an irrigation right was assigned. Such rights could be exchanged in a package with the land to which they were attached but could not be sold separately from the land. Once the Water Reform Agenda was enacted, states progressively established water plans for water resources throughout the MDB.

Another significant reform was development of the capacity to monitor and enforce volumetrically defined water rights across the MDB. Nearly all water rights in the MDB are now measured with meters. This reform, along with the establishment of a cap on issue of any additional water diversion entitlements for nearly all surface water bodies in the MDB, formerly instituted in 1995, led to the emergence of an active water market. An important outcome, as outlined in Sect. 6, has been significantly enhanced capacity to adaptively re-allocate water in times of drought, since water rights are no longer linked to a specific geographic location and water land use ratios are no longer administratively set. In Sect. 7, a conflict is described between a need to facilitate efficient, low transaction costs trade, and a need to protect environmental flows, that has not yet been fully resolved in the Australian water market. The last two sections present some ideas regarding institutional design that advance progress in design of water trade policy to protect environmental flows without introducing significant additional transaction costs.

20.4 The Murray Basin Water Market History

20.4.1 Permanent Water Rights Trade

The dynamics of the market for permanent water entitlements has been consistent with economic theory—water has traded out of districts with a predominance of low-value pasture lands (e.g., Goulburn, Loddon and Campaspe districts) and into areas with a comparative advantage in the production of high-value irrigated horticultural and viticultural production (Victorian and South Australian Murray). Over the decade (1997–2007), water entitlements have seen a 10 % decline in the Goulburn, and 5 and 6 % growth in the South Australian and Victorian Murray, respectively, as a result of trade in permanent water entitlements.[2] This is reflected in a shift in the use of irrigation water over the past decade. Between 2000 and 2001, and 2005 and 2006, total irrigated land in the Murray Darling Basin decreased by 9 %, but the area of grapevines increased by 35 % over this time period (ABS 2008).

Conjectures have been made that permanent water entitlement trade volume over this period would have been considerably greater in absence of several trade restrictions that still inhibit permanent entitlement water trade (Waterfind 2008). Until recently, trade of permanent entitlements out of New South Wales catchments was precluded, and total volumes per annum of permanent water entitlement trade out of Victorian catchments is limited. Additionally, to sell permanent

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[2] Calculations by the author are based on figures in Kaczan et al. (2011), Tables 2 and 7.

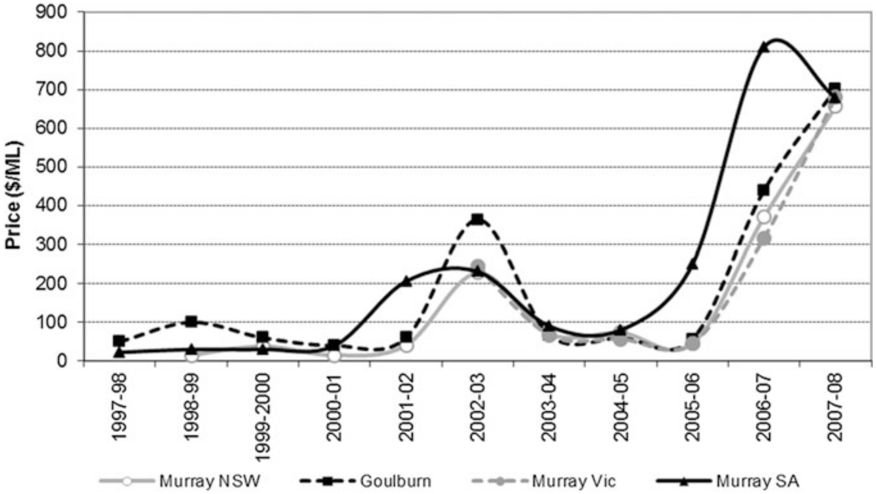

Fig. 20.4 Approximate prices for temporary water (allocations) averaged over the water season for four major trading areas in the southern Murray Darling Basin. *Source* (Kaczan et al. 2011)

entitlements in some districts, the water conveyance provider must be paid a significant termination fee associated with the costs of delivery system operations.

Several surveys suggest another reason for the paucity of permanent entitlement trades: a perception among irrigators that selling permanent water entitlements represents a loss of the opportunity to continue to hold an asset that is increasing in capital value (Bjornlund 2003); permanent water entitlements have displayed an increasing price trend over time, rising nearly five fold over the last decade (Fig. 20.4). This increasing price trend would appear to represent an expectation of increasing scarcity. Such expectation is in line with the projections for future water scarcity outlined by CSIRO (2008) and further analyzed by Kirby et al. (2013). However, part of the recent price rise is likely attributable to the Commonwealth government entering the market to acquire significant volumes of entitlement with the objective of restoring flows to maintain and enhance the environmental health of ecologically significant river floodplain and wetland and estuary assets. “The Living Murray” program was established in 2002 and was completed in 2009. Nearly 343 GL of permanent water entitlements were purchased over this period with an additional 163 GL planned before the end of 2009 (MDBA 2009). A further AU$ 3.1 billion in purchases, through the Commonwealth Government under the “Restoring the Balance” program, has also been underway since 2007 and is scheduled to continue through 2011. A result is that, the State and Federal Governments together are estimated to currently hold approximately 1200 GL of water entitlements (Wentworth Group, 2010).

20.4.2 Annual Water Rights Lease Market

The dominant form of water trade in the MDB is the annual lease of water allocations. In 2007–2008, an unprecedented one-half of all water allocations were traded: 82 % of trades were within catchments and 18 % were between catchments (NWC 2008). The volume of this trade is a clear indication that water can easily be traded on an annual lease basis with low transaction costs. Large volumes of trade took place through Internet trading sites that allow low transaction fees, nearly immediate (daily) transaction clearance and the water traded, generally available within a month.

Figure 20.5 shows the patterns of across catchment annual allocation trade and Fig. 20.6 shows the annual water allocation price dynamics. Regression analysis by Brennan (2006) estimates that two factors explain nearly 90 % of the variation

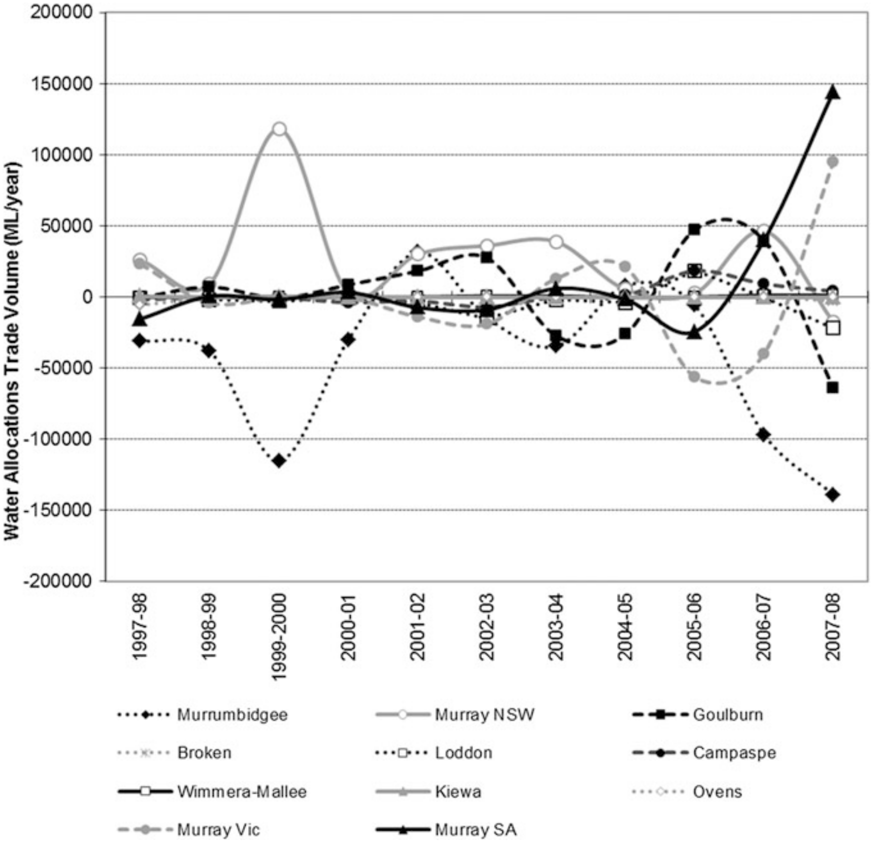

Fig. 20.5 Approximate annual trade volume of temporary water allocations in 11 major trading areas in the southern Murray Darling Basin. A negative trade volume indicates trade out of a region; a positive trade volume indicates trade into a region. *Source* (Kaczan et al. 2011)

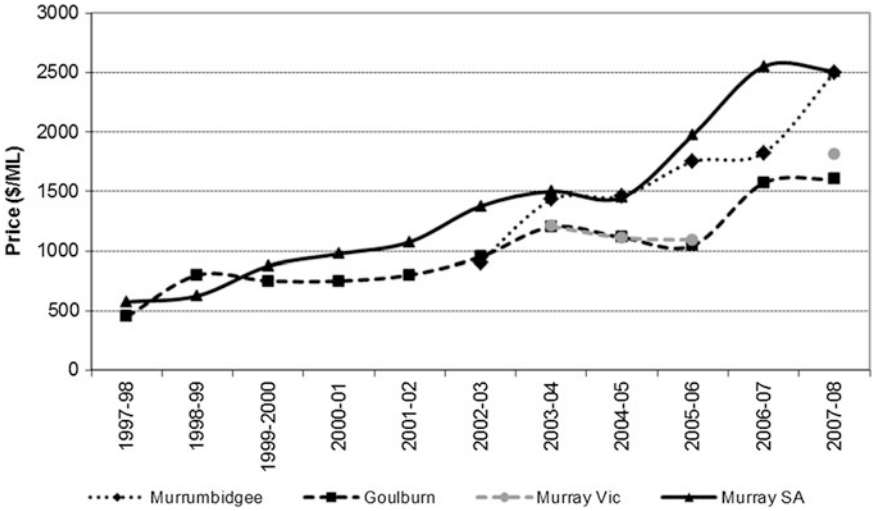

Fig. 20.6 Approximate prices for permanent, high security water (entitlements) averaged over the water season for four major trading areas in the southern Murray Darling Basin. *Source* (Kaczan et al. 2011)

in annual entitlement prices and trade patterns: the annual level of allocation (an indicator of the expected water scarcity level at the growing season outset) and growing season rainfall (an indicator of the divergence from initial expectation regarding the extent to which water requirements are likely to be met by rainfall).

The inverse relationship between price and allocation level can be seen by comparing Figs. 20.6 and 20.7. The price pre-season scarcity relationship is particularly evident in especially low water allocation years (2003–2004 and 2007–2008). The inverse relationship between volume traded and allocation level can be seen by comparing Figs. 20.5 and 20.7. Trade in low-allocation years is generally to high-value horticulture and viticulture (note the large volumes of trade into the Victorian and South Australian Murray where high-value wine and horticultural crops dominated in 2007–2008). The trends in the Goulbourn, a predominantly dairy region, exemplifies how dairy and livestock operations tend to grow pasture and forage in years of low-priced water and buy-in feed and trade away their water allocation in low-allocation, high-priced water years.

Volume traded and market price variation also can be related to within season patterns of rainfall and evapotranspiration. Irrigators with annual crops plant early in the season and sometimes trade based on their expectation of the deficit or surplus relationship between crop water requirements and their allocation. Those with perennial horticultural and wine plantings in contrast have less opportunity to adjust planted area annually. As the year progresses, if rainfall exceeds expectation, some irrigators end up holding allocations in excess of requirements, resulting in a drop in the price of water due to water surpluses. In years when rainfall is below expectations, prices tend to rise as a result of a relative shortage of water for critical mid-to late-season irrigations (Brooks and Harris 2008).

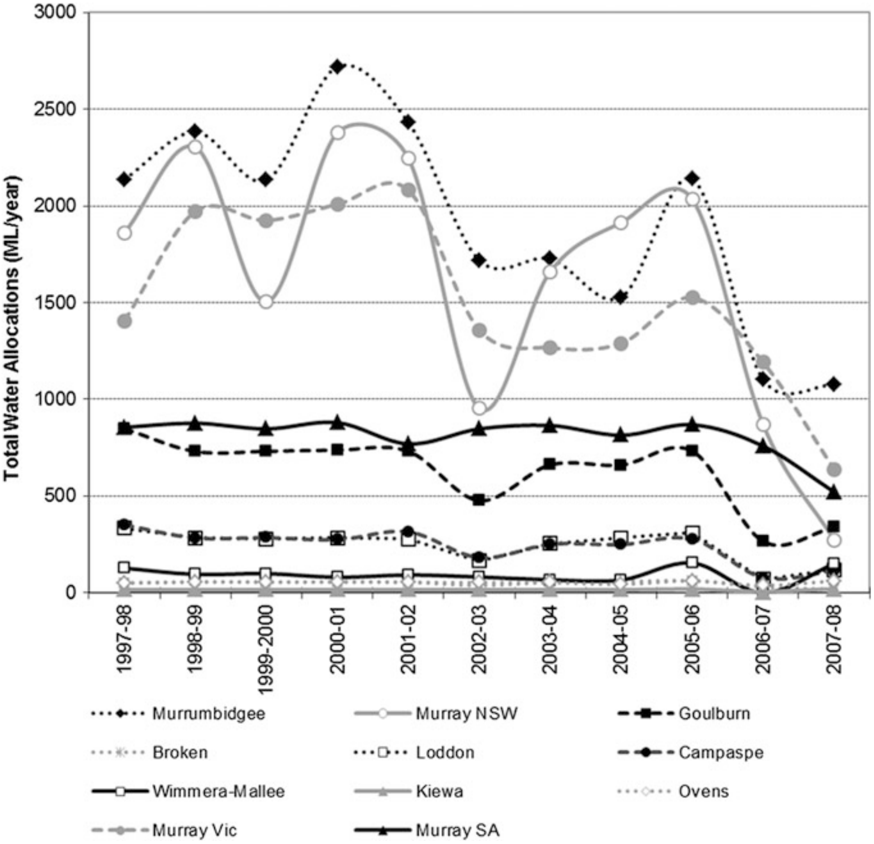

Fig. 20.7 Approximate annual allocation volumes in 11 major trading areas in the southern Murray Darling Basin. *Source* (Kaczan et al. 2011)

20.5 The Economic Benefits of Water Trade in Drought

Economists argue that water markets are efficient at allocating water during drought periods. The informational advantage of a market is that it can achieve efficient sharing with decentralized decision making. With water rights holders making individual decisions based on knowledge of water productivity in their own enterprises and observable price signals arising from collective market responses, a well-functioning market leads to an equilibrium market price and trade pattern. Those suffering the greatest marginal value loss as a result of reduced water allocation tend to buy additional water, as price tends to be less than the value of water in their production. Those suffering relatively little marginal value loss from reduced allocation sell water for an equilibrium price per unit greater than the potential value of a marginal unit of water in their enterprise.

Water market experience during the recent MDB drought is consistent with economic theory. The very high volumes of water trade are evidence that transaction costs involved are not high enough to be a significant trade barrier. For example, one-quarter of all irrigated farms participated in water trade in 2006–2007 (Ashton et al. 2009). Trade from low to high marginal value uses is also evident. The largest source of cross catchment water market supply was the Murrumbidgee catchment in New South Wales where water use is predominantly for comparatively low-value rice, pasture, and grain crops. Here, water trade led to the reduced diversion of 150 GL or 30 % of the total allocation to the catchment. The largest net demand in trade across catchments was the South Australian Murray, a region with greater than 70 % of irrigated area with relatively high-value permanent horticultural and viticultural plantings. Nearly 150 GL of water were traded into this region, thereby increasing the level of allocation by 35 %.

Several economics studies have estimated the benefits of water trade during drought conditions. Mallawaarachchi and Foster (2009) focused on 2007–2008 and estimated benefits to South Australia, the catchment with the largest net import of water, and the Murrumbidgee catchment in New South Wales, the catchment source of the largest net export. They estimated that the benefits of trade to South Australia were approximately $31 million while the benefits to upstream sellers in the Murrumbidgee were $4 million. This is likely an underestimate of the overall benefits of water trade given the focus on only two catchments, precluding benefits for about half of the volume of trade across catchments and the benefits from the 82 % of total trade that was within catchments. Further, the study assumed marginal value of water is likely low as it is based on a dated empirical study from a time of relatively more plentiful (and thus less valuable at the margin) water.

Peterson et al. (2004, 2005) estimated a AU$ 550 million benefit of water trade in the MDB in a dry year, considering benefits from both within and across catchment trade. Most of the benefit is estimated to result from trade within catchments and only about a quarter of the benefit (AU$ 138 million) is estimated to arise from trade across catchments. Connor et al. (2009) assess the economic impacts of the ability to trade water in mild, moderate, and severe climate change scenarios for the high-value irrigated horticultural and vineyard plantings in the Lower Murray region. They find that in a moderate climate change scenario (with a 38 % reduction in available water), net returns in Victorian and South Australian agriculture decline 19 and 54 %, respectively, in the absence of water trade but by only 5 and 11 %, respectively, with the possibility of water trade.

Using computable general equilibrium modeling, Dixon et al. (2008) estimated that the 2006–2007 drought reduced Australian GDP by 1.45 %. The value of completely free water trade within and across catchments in the MDB under 2006–2007 water scarcity conditions was estimated at AU$ 1.3 billion, including regional economy follow-on impacts. This may well be an overestimate of the level of benefits actually realized, as the assumed level of trade may overstate actual trade given several impediments to trade and with market transaction costs not fully accounted for in the model.

A limitation of all of the above-cited studies is that none includes estimates of the potential value of urban to rural water trading. Considering that major cities that could source water from the Murray and Tributaries (Adelaide, Melbourne, and Canberra) through water trade are considering major new urban water infrastructure, such as desalinization plants, to meet growing demand and as a contingency for drought, the benefits of such trade could be considerable. In any case, it seems reasonable to conclude that the benefits of water trade during recent MDB droughts have been considerable, likely in the range of several hundred million to over $1 billion annually during the last two to three years of operative drought. This is in comparison to a gross farm gate value of MDB irrigation of AU$ 4 billion in 2006–2007 (Ashton et al. 2009).

20.6 Adverse Environmental Flow Impacts of Water Trade

One incentive introduced with water trade has been for increased utilization of surface water that was previously left in-stream. Prior to water trade, water rights were attached to land and defined as an annually varying quantity of allowable water use per hectare of land. Bjornlund (2003) noted that 60 % of the irrigators responded to the separation of land and water rights by utilizing water previously left in stream in years of high allocation. With the introduction of water markets, many water allocations that had previously been unused (sometimes called sleeper or dozer rights) were traded from non-users to users, thus increasing overall water diversions (Lee and Ancev 2009). Prior to trade, some water rights tended to be left unutilized in relatively wet years: essentially this was a risk management strategy against shortage in dry years. After trade, the previously unutilized "sleeper" and "dozer" water became activated to place greater land areas of flexible annual crops under irrigation in wet years or to trade.

The advent of the cap on water allocation and water rights separate from land also introduced incentives to increase irrigation efficiency, as water saving could be used to expand irrigated area or sold on water markets. Available statistics show a dramatic decline in the rate of irrigation water application per hectare for Australia since introduction of water markets (and by inference, the MDB as the location of more than half of all Australian irrigation). Water use per hectare declined from 8.7 ml per hectare in 1996 to 4.2 ml per hectare in 2005 (OECD). As noted by Young (2008), this is a greater increase in irrigation efficiency than is reported for any other OECD country over these years. The extent of water "spreading"—increasing irrigation area through greater or more efficient utilization of water was evaluated by Bryan et al. (2009). They concluded that despite the cap on granting additional water rights, set in place in 1995, the amount of land irrigated in the MDB expanded by 20 % between 1995–1996 and 2000–2001. As the area irrigated contracted between 2001 and 2006 as the result of a reductions in allocations, the drive to increase efficiency (reduce water use per hectare) continued. This is evident in the less-than-proportionate 9 % decrease in irrigated land area for a 16 % decline in irrigation diversions over this period.

Another incentive established through introduction of a cap on surface water use and allowing trade in this resource was increased utilization of groundwater. It is estimated that groundwater extraction levels increased by 415 GL between the 1999–2000 and 2004–2005 cropping years in the basin. This represents a marked acceleration in previous historical rate of growth in groundwater extraction which grew by only 180 GL between the 1983–1984 and 1999–2000 cropping years (MDBC 2008).

A consequence of the increased efficiency and trade is that less flow was left in stream than when irrigation water rights were attached to land and not tradable. Several case studies estimated the impacts of reduced stream flow for parts of the basin. Qureshi et al. (2010) estimated that in the Murrumbidgee catchment, the opportunity to trade water introduced incentives to save 177 GL (8 % of diversions) through efficiency practices and to sell or “spread” the water savings. They concluded that most of the increased efficiency would have reduced drainage and return flows to the environment. Connor et al. (2009) estimated that the incentive created by the introduction of water markets in the Lower Murray region would have been sufficient to induce efficiency savings of 113 GL (11 % of regional irrigation diversions) and reduce irrigation drainage and return flows by 50 %.

20.7 Principles for Efficient and Environmentally Sustainable Water Markets: What Have We Learned from the Australian Experience?

The story of the Murray Basin summarized above is that reforms in the 1990s resulted in defined, enforced and monitored water rights tradable independently of land. This led to very active water markets that during the recent severe drought, very effectively re-allocated water from lower- to higher-value uses and significantly reduced the drought’s economic consequences. The significant incentives to utilize water that had previously been left in-stream and to irrigate more efficiently, however, led to reductions in water available for the environment.

One nuance of Australian water policy is that the quantity of water defined as tradable is the allowable diversion, consisting of both a portion that is consumptively used and a portion that returns to ground or surface water as drainage or runoff. This is very likely an important reason that water markets arose so quickly in the MDB and also a reason that these markets led to an erosion of flow available for the environment. The interdependence among water rights that arises because return flow from upstream diversions form the basis for downstream rights has long been understood (e.g., Hartman and Seastone 1965).

To avoid the adverse environmental flow consequences of water trade that can arise as they have in Australia, tradable water rights in some other parts of the world are described as the consumptively used portion of diversions. This avoids erosion of return flows that form part of downstream water rights. In places like the western United States there is, at least in principle, a requirement that water trades do not diminish return flows and thus avoid erosion of downstream consumptive or environmental water rights.

While such a water rights definition avoids the problem of water trade diminishing the value of downstream water rights, the way that such approaches are typically implemented tends also to involve resolution of conflicts in the courts, which tends to increase water trade transaction costs and reduce the potential economic benefits. This is because consumptive use and return flow are much more difficult to monitor than diversions, and thus typically much more highly contestable. A classic water allocation dilemma thus arises (Howe et al. 1986): (a) define water rights to protect third parties but in a high-transaction costs way that reduces benefits of water trade, or (b) choose a simpler definition that facilitates low-transaction cost trade without as much concern for third-party water rights. It can be argued that in implementing tradable water rights, Australia has essentially chosen path b.

Going forward, one alternative to insure against reduced environmental flows as a consequence of future water trade in the MDB is the approach used in the western United States described above. Young and McColl (2002) suggest an alternative approach involving periodically reviewing the overall impact of water trade on in-stream flows and adjusting allocation rules in water plans, reducing allowable diversions so as to preserve environmental flow.

The advantage with this approach is that it maintains the benefits of the efficient water market that are possible with trade in easily monitored and not easily contested water diversions. Yet, it also addresses the issue that defining tradable water rights as diversions can tend to erode environmental flows. The highly contested environmental flow issue is addressed for an accumulated result of many individual trades in an occasional periodic process (once every 5 years in the Australian case). All of the expensive science and public processes in reaching decisions about periodic revisions of allocations is concentrated and addressed primarily by bureaucracies with specialized technical capacity. Thus, the impasse and stifling of water trade created by individually contestable water transfers, a feature of some other systems, is avoided.

20.8 Summary and Conclusions

Institutional reforms in Australia over the 1990s resulted in volumetrically defined and metered water rights independent of land that are tradable. These water rights are fully defined in all states of water availability through the inclusion of two elements in their definition: (1) a water access entitlement—"a perpetual or ongoing entitlement to exclusive access to a share of water from a specified consumptive pool as defined in the relevant water plan"; and (2) an annual water allocations, defined as a "specific volume of water allocated to water access entitlements in a given season, defined according to rules established in the relevant water plan."

The result of these well-defined water rights, tradable independently of land, has been the emergence of efficiently functioning markets, especially for the annual lease of water allocations. An astounding one-half of all water allocations were traded in the extreme drought year of 2007–2008, primarily from low-value annual crops and pasture to high-value horticultural and wine crops. Estimates of the benefits of the re-allocation that these transactions afford are as high as $A 1.3 billion, including regional multiplier impacts in the context of an irrigated agricultural sector gross regional product of $A 4 billion.

On the downside, the introduction of water markets has led to a decrease of instream flow, due to increased utilization of previously unutilized water and increased irrigation efficiency; more area is under irrigation with more efficient irrigation, thereby leading to less irrigation drainage return flow back into the river and for the environment. While the extent of reduced environmental flow has not been assessed comprehensively at the basin scale, there is significant evidence consistent with the hypothesis. The evidence includes surveys showing a halving of water application rates, a 20 % expansion of irrigated areas, despite a cap on growth in irrigation diversions, and case studies suggesting in the order of 60 % of diversions saved through efficiency measures used to more extensively irrigate.

Striking a balance in institutional arrangements to allow the benefits of low transaction costs trade, but avoiding the adverse environmental flow consequences poses a classic dilemma: (a) define water rights to protect third parties but in a high transaction costs way that reduces benefits of water trade, or (b) choose a simpler definition that facilitates low transaction costs trade without as much concern for third-party water rights. It can be argued that in implementing tradable water rights, Australia has essentially chosen path b.

Going forward, the issue for Australia and other countries that are contemplating the introduction of water trade is how to resolve this dilemma. One alternative might involve periodically reviewing the overall impact of water trade on in-stream flows and adjusting allocations to preserve environmental flow. This could maintain the benefits of the efficient water market enabled by trade in easily monitored and not easily contested water diversions. Yet, if this approach is taken, one should be cognizant of the issue that defining tradable water rights as diversions can tend to erode environmental flows. The alternative, it seems, is to define water rights in terms of consumptive use, but that would seem to introduce excessive transaction costs into the market, costs that could stifle trade.

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Chapter 21
Drought Management Strategies in South Africa and the Potential for Economic Policy Instruments

Rashid Hassan

Abstract Previous drought management strategies in South Africa relied on more reactive short-term response approaches of providing post-drought relief and introducing restrictions on water supply during low-flow periods. Recent efforts have recognized the importance of adopting a more proactive approach to managing drought as an integral part of regular climate variability, and agricultural production planning and management decision-making. The new drought management plans developed and being implemented, however, make little use of economic policy instruments to promote self-reliance in managing drought risk. This chapter points to the high potential for economic policy instruments in shaping economic incentives in South Africa to induce desirable long-term drought self-adaptations, as well as sustainable farming and water and land use practices.

21.1 Introduction

According to its climatic features, South Africa is considered a semi-arid country vulnerable to water stresses, particularly drought. The country developed sophisticated macroeconomic and water management infrastructures that enhanced its ability to cope with water stress situations, including drought episodes. Drought management strategies and policies in the country have also seen important evolutions over the past few decades. The South African water sector in particular has been witnessing radical policy reforms since 1994 that have important implications for drought management. This chapter reviews the evolution of the policy environment and experiences gained in managing drought in South Africa. It then

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attempts to investigate to what extent economic policy instruments have been used so far and what potential these policies hold for managing drought in South Africa.

The next section provides an overview of key climate attributes and droughts in South Africa. Section three reviews how droughts have impacted the country's economy and people. Section four traces the evolution of drought management strategies and policies in the country, and discusses their effectiveness and deficiencies. The potential for the role of economic policy measures for managing drought is discussed in Sects. 5 and 6 concludes with policy recommendations.

21.2 Droughts in South Africa

South Africa receives on average about 500 mm of rainfall per year with huge disparities in its spatial distribution, ranging from as little as 2.5 mm on the west coast to more than 1,000 mm on the east coast (Fig. 21.1). It is estimated, however, that about 65 % of the country receives lower than this average amount of rain, and more than 20 % of the country receives less than 200 mm/year of rain (Schultze 1984; DWA&F 1986; Tyson 1986). Spatial variability in rain seems to follow similar spatial patterns with the low rainfall areas of the east showing the highest variances (Fig. 21.2). Two distinct rainfall-generating mechanisms characterize the country's climate: a summer rainy season dominates the central plateau and eastern coastal areas, and winter rains fall in the southwestern region.

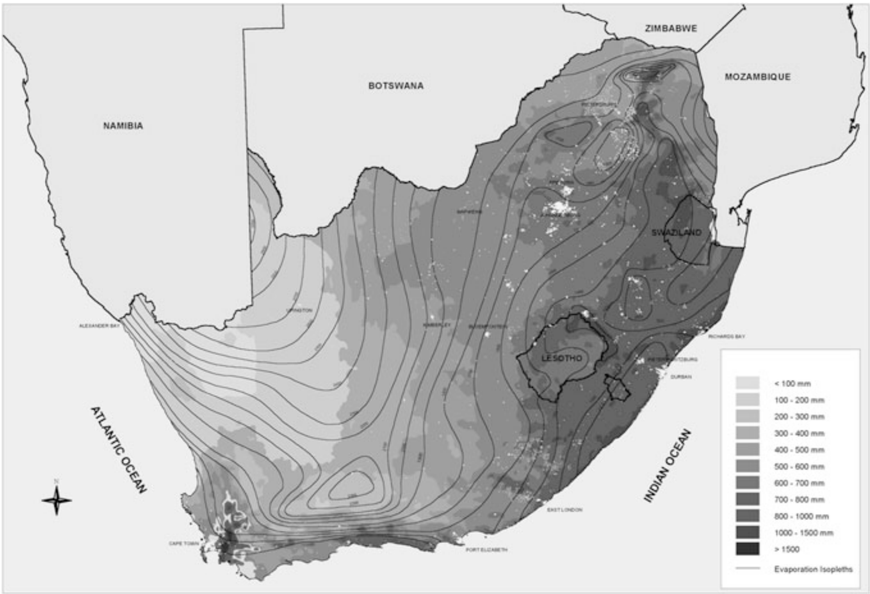

Fig. 21.1 Rainfall and evaporation

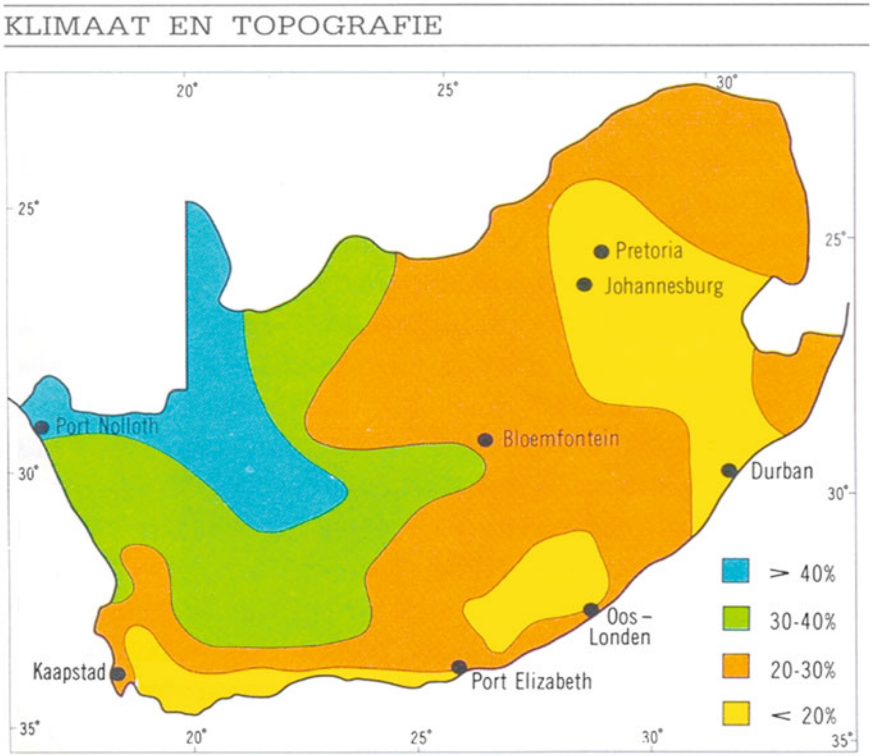

Fig. 21.2 Percentage deviation from mean annual rainfall

Recorded droughts have been experienced since the early 1800s in the winter rainfall regions of South Africa (known then as the British Cape Colony) (Ballard 1986). Prolonged droughts have also been reported during the 1820s in summer rainfall regions, particularly Zululand and Natal, with major political ramifications for the region. Recent analysis of the spatial and temporal distribution of droughts shows that South Africa experienced below-average rainfall during all decades of the past millennium, except for the 1950s and 1970s (Frik Cornelius personal communications 2009). Frequency and duration of drought have shown worsening trends in recent years, as the country received below-normal (mean) rainfall for seven out of the 11 seasons between 1982 and 1993 (Laing 1994; Rouault and Richard 2003). The 1981–1983 and 1991–1993 periods represent the only times over the preceding 70 years when drought prevailed over two consecutive summer seasons (Laing 1994). Dry years were found to be highly correlated with El Niño years in South Africa (van Heerden et al. 1988; Lindesay and Vogel 1990; Mason et al. 1994).

Not all regions, however, receive below-average rain at the same time, and important spatial variations have been observed in terms of the extent and severity of droughts. Based on precipitation data, Zucchini and Adamson (1984) developed models to map the spatial distribution of droughts in the country. Their work confirms spatial variations in the extent and severity of droughts experienced between 1921 and 1983. While the droughts of the late twenties (1927–1928), early thirties (1932–1933), mid and late forties (1944–1945 and 1948–1949) and early eighties (1981–1983) were widespread, the severe droughts of 1925–1926 and 1963–1965 mainly affected the central interior. On the other hand, south-western cape coastal areas suffered severe droughts during 1926–1928 and 1972–1973 when, during that same period, the central interior experienced flooding (Zucchini and Adamson 1984). Nevertheless, the above suggest that inter-annual variability in precipitation is inherent and drought is equally a recurrent feature of the South African climate.

21.3 Drought Impacts on the South African Economy

Most of the above results on drought patterns are based on analysis of precipitation data. While rainfall deficiency, measured as a deviation from the normal average, is the main indicator typically used as the trigger of what is known as meteorological drought (MD), that does not necessarily translate into agricultural drought (AD) or hydrological drought (HD) (Wilhite 1993, 2000). Many factors come into play before an MD leads to an AD or an HD. AD relates to whether there is sufficient soil moisture to support an agricultural production activity over its season (generally between three and six months). This depends in the first place on the type of agricultural activity that determines desirable quantity and timing of moisture availability. Moisture availability, for instance, is a function of evapotranspiration rates, which in turn depend on temperature and wind variables. Also, certain stages of plant growth, such as flowering, are highly sensitive to moisture stress than others, and hence the importance of timing and duration of rain for occurrence of an AD. On the other hand, timing of rainfall is less important for defining an HD, which is determined by stream-flow deficits and levels of water in rivers, reservoirs and aquifers. HD is therefore typically triggered by longer-term rainfall deficiency episodes of six to 12 months duration (Wilhite 1993).

Other important factors that influence the impacts of droughts and moderate the progression of MD to AD or HD include the water supply management system and infrastructure, the policy environment, and institutional support structures in place. The surface water supply and allocation system is highly managed in South Africa, as the country has developed an extensive inter-basin water transfer and water storage infrastructure. These enabled the country to regulate water flow (surface water yield) and provide supplementary irrigation water to mitigate soil moisture stress in deficient rainfall regions (i.e., experiencing an MD). The current infrastructure and policy and institutional environment for water management and agricultural services, however, suffers from inherent biases in favor of large commercial farming and urban industrial establishments, compared to access enjoyed by other segments of the population, particularly previously disadvantaged rural and peri-urban poor.[1]

Nevertheless, droughts inflict significant damages on the South African economy and its people, particularly the more vulnerable poor. While other natural disasters such as floods, storms, and fires cause much higher direct damages to economic assets and human life than droughts, their impacts are usually confined to specific areas and time periods as they recede quickly. Droughts, on the other hand, impact larger areas and persist over longer periods, causing significant indirect socioeconomic damages. The types of socioeconomic impacts of droughts experienced in South Africa include negative impacts on agriculture and farm incomes, food security through reduced crop yields and quality of grazing (affecting livestock productivity), reduced power generation capacity, increased forest and range fires (affecting vegetation, wildlife and ecosystems). Additionally, drought negatively affects general household welfare in terms of water scarcity, forced migration, and health implications (Vogel et al. 1999).

The 1991–1992 drought, for example, caused failure to 70 % of the crops, death of large numbers of livestock, and exposed half of the population in affected areas to the risk of malnutrition (van Zyl 2006). Effects of droughts also translate into large impacts on the macro economy (Benson and Clay 1998). Economic growth slowed down by between 0.5 and 1.2 % as a result of the 1982–1983 and 1992–1995 droughts (Finance Week 2002). Maize imports during the 1992 drought reached US$604 million, whereas, earnings from agricultural exports dropped by about US$250 million, and the gross domestic product (GDP) fell by 2.4 %. The said drought also was estimated to have caused a fall of 27 %, 8.4 %, and 4.2 % in agricultural GDP, gross domestic savings, and gross domestic investments, respectively (Pretorius and Small 1992).

Many lessons were learned from these droughts that influenced introduction of major recent reforms to the country's drought management strategies and policy, as discussed below.

21.4 Drought Management Strategies and Policies in South Africa

Since different agencies have borne the primary responsibility for managing agricultural drought and hydrological drought, using different approaches and mechanisms, we present the subsequent review according to the two types of drought separately.

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[1] It is estimated that irrigated agriculture contributes 25 to 30% of total national agricultural output in South Africa from about 1.5 million ha on which an estimated 1 million subsistence farmers and 10,000 commercial farmers are dependent as the main source of income (WRC 1996).

21.4.1 Managing Agricultural Drought

The primary responsibility for managing agricultural drought (AD) rests with the National Department of Agriculture (NDA) and its regional branches at provincial and district levels. Prior to 1980, AD in South Africa was managed as an abnormal disaster event that required emergency government assistance. This reactive approach of crisis management focused on providing relief to the livestock subsector in regions declared as disaster drought (DD) areas, with little if any provisions extended to assist crop farmers. This was based on the assumption that 85 % of the country was under pasture land in dry zones that were prone to drought and also the assumption that crops belonged to what was termed "insurable assets," which did not qualify for relief assistance (Bruwer 1990, 1993). Under this strategy, a phased approach was followed to provide assistance to livestock farmers in designated DD areas. In the first phase, which coincided with the onset of declaring an region a DD area (trigger), a rebate on transport costs was provided to farmers to subsidize importation of feed from, and/or movement of animal stocks to outside proclaimed DD regions. Phase two would set in if conditions in affected areas continued to worsen and, hence, require loans through the Agricultural Credit Board. The need for direct government subsidy to support buying of feed would kick in at phase three, at which time conditions continued deteriorating (Bruwer 1990).

Several difficulties are apparent with the above-described drought management scheme. First, the criteria used to define a trigger for declaring an area DD was based on subjective meteorological drought (MD) indicators. It is noted, for example, that many districts have been proclaimed DD areas for more than 50 % of the time, versus the research-based MD occurrence of less than 35 % (Skinner 1981; Roux and Opperman 1986; Booysen and Rowswell 1983). Second, one can see the difficulty with the subjectivity of delineating different relief phases for provision of the needed assistance. Third, this strategy believed to have discouraged adaptation responses and failed to promote self-reliance among farmers who remained highly dependent on public funds for assistance.

This strategy was accordingly considered ineffective, as it did not achieve notable reductions in the vulnerability of affected communities or bring about improvements in the resilience of the natural resource base, in which degradation continued (Bruwer 1990; Smith 1993). Other concomitant global changes also necessitated a shift in the approach and attitudes towards drought management, such as the decline in the importance of agriculture in national economies and the political power of agricultural lobbies, globalization, and increased awareness of the high environmental costs of extensive and intensive expansions in agriculture, and the realities of climate change dynamics (O'Meagher et al. 1998). Important improvements, therefore, were introduced in the 1980s.

Most important among the improvements in drought management policies of the 1980s are the more objective DD assessment procedures, and eligibility criteria introducing measures and incentives to discourage overstocking, reducing the pressure on the natural resource base, particularly grazing and water resources. Under the new drought management policy, DD is assessed based on more stringent meteorological assessment criteria as well as on other aspects related to conditions of the stock, and availability of water and forage for grazing. Only those who comply with maintenance of a nucleus herd (defined as two-thirds of the official carrying capacity) qualify for assistance. Finally, the process was better institutionalized by establishing drought committees at national and district levels to assess eligibility of applicants for assistance, based on the more comprehensive criteria outlined above. Assistance provided to those who qualify includes monetary incentives for stock reductions and maintenance of nucleus herd; subsidies for lease of grazing outside proclaimed areas for feed and transport costs; and low-interest credit (Anon 1985; Bruwer 1990; Smith 1993).

Improvements in AD management strategies continued towards the early 1990 s through introduction of more stringent DD assessment criteria and eligibility requirements. The main purpose for these adjustments was to promote more self-reliance in coping and adapting to drought risks that are inherent in the recurrent climate and should be an integral part of regular farm management and planning decision-making. This necessitated denial of public assistance, except for compensation for a genuinely abnormal DD circumstances under very stringent eligibility criteria (O'Meagher et al. 1998). Some additional incentives have also been introduced, such as subsidies on water quotas and incentives for conversion of cropland into pastures (Bruwer 1993).

Other problems remained with AD management strategies, such as ineffectiveness in promoting self-reliance and private adaptive responses, lack of adequate DD assessment procedures and programs including monitoring schemes (i.e., weather stations' networks), poor capacities in coordination of relief efforts, lack of dissemination of the correct information, creation of appropriate awareness, and preparedness for coping with drought. Crop farmers continue to be largely left out and must rely on weather insurance and derivatives, which had attracted only a few large commercial fruit, wheat, and maize growers (Bolinn 2002). The most important issue with these AD schemes and policies is the fact that they were all directed primarily towards, and mainly benefited, large commercial farmers while not satisfactorily addressing the needs of emerging farmers and the more vulnerable rural poor in general.

Public policy, particularly in the water and agriculture sectors, has seen major shifts since 1994 that contribute to addressing many of the problems noted above regarding drought management in South Africa. The White Paper on Agriculture (NDA 1995), White Paper on a National Water Policy in South Africa (DWA&F 1997), Discussion Paper on Agricultural Policy in South Africa (NDA 1998), and White Paper on Disaster Management (DCD 1998), all advocate a new approach and strategy in managing drought. The new direction of public policy on drought management emphasizes a shift towards a more proactive approach that adopts risk reduction rather than the reactive drought relief strategy of the past (Backeberg 2003). It is based on self-reliance in coping with drought events that are inherent in the normal climate cycles, integrating risk management in regular farm management and planning decisions, and moving away from short-term crises management to long-term strategic planning. This requires major changes in the structure of economic incentives to promote more sustainable agricultural land and water use practices. It also requires significant structural adjustments in the policy and institutional environments, assignment of roles and responsibilities, financing, investment strategies, appropriate information generation and dissemination systems, research and capacity building at local, regional, and national scales.

Progress in this direction has been made through establishment of the National Disaster Management Centre (NDMC) in 2006, following stipulations of the Disaster Management Act (DMA) No. 57 of 2002 (RSA 2002), which provided the framework for disaster management including DD in the country. This was followed by development of the Agricultural Disaster Risk Management Plan (ADRMP) (DA 2008a) and the Agricultural Drought Management Plan (ADMP) (DA 2008b) as mandated by the DMA. Both of these were at their draft discussion paper phase at the time this book was published. Components of the ADMP of relevance to the issues in this chapter will be addressed in Sect. 5 below.

21.4.2 Managing Hydrological Drought

South Africa has developed a huge water storage infrastructure to adapt to the arid conditions and high inter-temporal variations in rainfall that characterize its climate. If not properly regulated, large variations in rainfall would lead to even larger variations in river flows. Under high rates of evapo-transpiration and evaporation in such arid climates, soil moisture is depleted rapidly before river flow can occur, which may lead to hydrological drought (HD) situations. This necessitates storage of water during wet periods to make available later at times of low flow. Capacity to store water is particularly important for managing HD when river flow becomes very low for consecutive years.

In addition to the extensive network of dams and large water storage capacity (37 billion m^3 in 2000, Hassan and Crafford 2006), the country developed a comprehensive inter-basin water transfer infrastructure to move water from surplus to deficit regions (Tables 21.1 and 21.2). This enabled South Africa to cope with the high spatial variability in rainfall in the country and manage the large regional imbalances between local demand and supply of water created by its past economic development and population growth trends. Nevertheless, water deficit situations currently exist, even under normal average rainfall situations in many water management areas (WMA), placing significant pressures on the ecological reserve in these regions (DWA&F 2004; Hassan and Crafford 2006). This situation of water stress is expected to get worse with further economic development plans and predicted climatic changes in the near future.

The Department of Water Affairs (DWA) has the primary responsibility for managing HD. It collaborates with the National Department of Agriculture (NDA), the NDMC and other national, regional and local authorities, such as water and

Table 21.1 Existing natural and manmade interregional water transfers

	Total water transferred (mil. m^3)	Share of transfer in… (%)	
		Sending region	Receiving region
Total interregional water transfers	5,528	–	–
Water transfer schemes	1,415	–	–
Orange River Project			
From Upper Orange to Fish-Tsitsikamma	714	17.4	50.8
Thukela-Vaal transfer schemes			
From Thukela to Upper Vaal	431	49.7	34.8
Lesotho Highlands Water Project			
From Lesotho to Upper Vaal	270	n/a	10.8
Major river-based transfers	3,962	–	–
Vaal river			
From Upper Vaal to Middle Vaal	799	32.1	73.7
From Middle Vaal to Lower Vaal	603	55.6	49.2
Orange river			
From Upper Orange to Lower Orange	2,360	57.6	90.0
Breede river			
From Breede to Berg	200	26.7	18.3

Source Hassan et al. (2008)

irrigation boards, municipalities, water users' associations, and catchments management agencies. The country is divided into 19 WMA's (Fig. 21.3) over which the above-described interconnected water storage and conveyance system spreads. The National Water Act (NWA) of 1998 (RSA 1998) stipulates the establishment of a catchment management agency (CMA) for each water management area to manage water resources within that region. The NWA also requires that protection, use, and development of water resources be guided by national water resources' strategy (NWRS), based on CMA level internal strategic perspectives—ISPs (DWA&F 2004). The National Water Policy (DWA&F 1997) established and is implementing guidelines for managing bulk water supply systems under normal and drought conditions (DWA&F 2006).

Over the years, the basic principles of managing HD in South Africa have been based on restricting withdrawal of water from the regulated flow (yield) of the bulk water supply system during low-flow periods. A host of modeling and decision support tools, such as the short-term characteristic curves (STCC), water resources yield and planning models (WRYM & WRPM), reserve determination and management models (RDMM), and various other regional water flow modeling tools, the monitoring and reporting branch of DWA&F provides the information needed by water resource managers at national and regional levels to restrict water abstraction. The restrictions are different for different water supply schemes, depending on the severity of shortfalls and reductions in yield and flow levels, and

Table 21.2 Water supply and use in South Africa by water management areas in 2,000 (units are in million m^3)

Water management area	MAR	Ecological reserve	Yield			Transfers in	Use		Transfers out	Water balance
			Surface water	Ground water	Return flows/effluent		Production	Households		
Limpopo	986	156	160	98	23	18	280	42	–	(23)
Luvuvu/Letaba	1,185	224	244	34	23	–	297	36	13	(36)
Crocodile-West/Marico	855	164	203	146	369	519	889	295	10	43
Olifants River	2,040	460	410	99	100	172	868	97	8	(192)
Inkomati	3,539	1,008	816	9	71	–	787	58	311	(260)
Usuthu to Mhlatuze	4,780	1,192	1,019	39	52	40	667	50	114	319
Thukela	3,799	859	666	15	56	–	288	46	506	(103)
Upper Vaal	2,423	299	599	34	501	1,311	669	376	1,379	19
Middle Vaal	888	109	(67)	57	62	829	310	60	502	6
Lower Vaal	181	49	(54)	125	54	548	599	44	–	30
Mvoti to Umzimkulu	4,798	1,160	433	6	84	34	510	287	–	(240)
Mzimvubu to Keiskamma	7,241	1,122	776	21	57	–	297	77	–	480
Upper Orange	6,981	1,349	4,311	65	71	2	881	87	3,149	333
Lower Orange	502	69	(1,083)	25	97	2,035	1,009	19	54	(8)
Fish to Tsitsikamma	2,154	243	260	41	122	575	855	46	–	97
Gouritz	1,679	325	191	64	20	–	301	37	1	(64)
Olifants/Doorn	1,108	156	266	45	24	3	365	8	–	(35)
Breede	2,472	384	687	109	68	1	600	32	196	37
Berg	1,429	217	380	57	45	194	444	260	–	(28)
RSA	49,040	9,545	10,217	1,088	1,899	–	10,915	1,958	170	186

Source DWAF (2004) and StatSa (2006)

Fig. 21.3 Water management areas (WMA)

the requirements profile of users relying on each particular water supply scheme (DWA&F 2006). If low storage levels persist in subsequent years, suggesting an HD, more severe restrictions need to be imposed.

Guidelines are issued by the operations division and chief director regions of DWA&F to managers of the various water reservoirs and supply schemes. Managers

Table 21.3 Curtailment levels on water supply in the Vaal and Western cape water systems

	Restriction levels			
	0	1	2	3
Acceptable frequency		1 in 20 years	1 in 100 years	1 in 200 years
Restricted demand (% of normal)	100 %	80 %	70 %	50 %
Vaal water supply system		90 %	70 %	40 %
Domestic	100 %	80 %	70 %	50 %
Industrial		100 %	100 %	100 %
Irrigation		100 %	100 %	100 %
Strategic		90 %	70 %	50 %
Western cape water system		100 %	90 %	60 %
Domestic		90 %	70 %	50 %
Industrial		100 %	100 %	100 %
Irrigation				
Strategic				

Source Adapted from DWA&F (2006)

then set dam operation rules and issue specific regional or scheme-level restrictions to the public and various user groups in each region. Restrictions on withdrawal during drought are guided by strategic priorities of the ruling water policy framework at the time, which have radically changed under the new National Water Policy (DWA&F 1997) and NWA. The current water policy places higher priority on meeting reserve requirements, which constitute provisions for basic human need and ecological demand, where lowest curtailments are imposed. The NWA also gives priority in water allocation to strategic users, such as power generation and key industries. Irrigation receives highest reductions in water supply during drought, whereas domestic users, particularly rural communities and low-income urban dwellers are less curtailed. Examples of restrictions on water supply from the two largest water supply systems in the country are presented in Table 21.3. It is clear from Table 21.3 that while both systems have similar curtailment levels for domestic and irrigation uses, the Vaal system of Gauteng is more restrictive on water allocations in drought years, particularly for industrial uses.

21.5 The Role of Economic Instruments for Managing Drought

In light of the experiences of the most severe droughts that hit the country in the early 1980s and 1990s, major efforts have recently been placed on improving drought management in South Africa. Establishment of the NDMC and development of the ADRMP and ADMP (DA 2008a, b) represent a big step forward in this regard. While these efforts recognize the need to adopt a more proactive approach to drought risk management, emphasis remains largely on dealing with information and institutional failures, and lack of preparedness experienced in responding to the recent droughts. Paying more attention to the role of generation and dissemination of better information for more accurate assessment, monitoring and effective early warning and awareness, while reforming legislation, public policy and institutional capacities to improve coordination and efficacy of relief efforts and recovery assistance, all focus on improving emergency response capacity. Although these are necessary improvements in preparedness for managing post-drought crisis, they are basically short-term response measures.

In spite of advocating a strategic shift in approach to the more important long-term goals of drought risk management, the recently developed drought management plans remain with the critical challenge and task of developing specific policy measures to promote self-reliance and sustainable farming and water and land use practices. Of particular importance is the potential for policy measures that would alter the structure of economic incentives in favor of desired changes in planning and management decisions of affected individuals and communities. For example, apart from a few recent examples in AD management, such as the subsidy to encourage stock reductions among livestock producers, little use has been made of economic policy instruments to manage drought in South Africa. Even the incentive scheme to reduce stocks, which reduces the pressure on grazing resources and pasture land, leaves out livestock farmers who are not located in DD proclaimed areas. It is therefore important to extend such incentive schemes to induce similar desirable adjustments in livestock production practices outside DD areas.

Additionally, crop farmers are largely excluded from AD management programs. For example, a huge gap remains in developing instruments and institutions that would enable sufficient numbers of crop farmers to participate in yield and weather insurance markets that currently attract a handful few of commercial crop farming enterprises in South Africa (Bolin 2002; Douglas-Jones 2002). Formal agriculture insurance, and drought insurance in particular, have been inaccessible to poor farmers in the developing world in general. However, successful experiences do exist in making micro-insurance work for poor farmers in developing countries (Sakurai and Reardon 1997; Skees et al. 1999; Diaz Nieto et al. 2006). This is an area that needs urgent attention and coordinated efforts to provide access to emerging small farmers in very marginal environments. Self-insurance options should be made available to them, such as entry into off-farm income and employment opportunities when drawing on their own assets and savings are seriously limited.

Economic policy instruments for promotion of sustainable farming, water and land use practices are also not well exploited to induce desirable longer-term adaptations to drought in South Africa, especially if one considers the grim predictions of drier and hotter future climates for the drought-prone regions of the country. For instance, currently no policies and programs exist that provide incentives or subsidy schemes to promote adoption of more efficient water use technologies, such as sprinkler and drip irrigation methods among other water-saving farming practices. On the contrary, it appears that most recent agricultural development efforts plan for further expansions in relatively more water-intensive crops and land use options (Seymour and Desmet 2009).

The current water allocation and tariff system also does not encourage voluntary water savings. This is because water quotas are based on licensed land area on which fixed tariffs are charged in advance, irrespective to whether farmers use their allocations or not. This provides no incentive to farmers to conserve water. A better charging system is one that charges for actual water usage but requires implementation of metering systems. In absence of water metering, however, some innovative schemes can be devised and used to encourage voluntary water savings through a rebate system that gives credit for using less than the full quota allocation. Rebates could be in the form of direct cash compensations or a credit allowance (permits) to be carried forward for future use, or that could be traded.

Hydroelectric drought management is currently based on restrictions in physical water supply during low-flow periods and makes no use of potential economic policy measures for inducing voluntary adjustments in water abstraction by users. The DWA&F, for instance, does not apply a special higher levy on bulk water supply during drought periods to discourage overuse. Similarly, municipalities rely on monitoring and legal enforcement measures, such as fines and penalties that are very expensive to administer, instead of applying a special higher tariff system for rationing water use, particularly for low-priority domestic purposes (e.g., gardening, car washing) during drought periods.

One of the major challenges facing drought management in South Africa is protection of the welfare of highly vulnerable poor households in rural areas in which there is no access to assured water supplies (i.e., pipe, borehole and watering point systems). These communities typically experience high prices for acquiring water from venders during drought. It is estimated that currently only 1.4 % of total surface water yield is available to cater to these groups (Blignaut et al. 2009). Plans for provision of access to assured water supplies to the rural poor and their livestock need to be rapidly implemented, but must apply economic incentives to discourage over use and wasteful consumption.

21.6 Conclusion and Recommendations

Policy and practice of drought management in South Africa have evolved over the past few decades from a more reactive crisis-relief response strategy to a more proactive approach advocating self-reliance in managing drought as an inherent climate risk and integral part of the long-term planning and decision-making process. Nevertheless, current efforts to manage both AD and HD risks in the country remain highly reliant on more regulatory command and control measures, making little use of economic policy instruments that promote voluntary adoption of more sustainable farming, and water and land resources conservation practices. It is clear that economic policy instruments hold the potential for altering economic incentives in favor of desirable practices that promote self-reliance and voluntary adaptation measures to enhance the long-term adaptive capacity and resilience of natural and social systems vulnerable to drought in South Africa. This chapter proposes the use of subsidy schemes and credit rebates to encourage adoption of water and land use methods that are less water-intensive and more suited to drought conditions. Major efforts are needed to design more effective drought-risk insurance schemes that will provide better access for emerging small farmers. It is clear that carefully targeted research evaluating merits and disadvantages, preferably based on some cost-benefit assessments of alternative economic policy options for drought management is necessary to help policy makers and water managers prioritize and properly sequence their choices and actions.

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Part V
Water Management and Policy

Chapter 22
Some Considerations Regarding Water Management in Mexico: Towards an Integrated Management System

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Abstract This paper describes the situation of water resources in Mexico in terms of scarcity, inequality and pollution, and explains how water management has changed in the country through time, responding to international best practices and to intentions to overcome difficulties. The paper tries to show that despite recent policy efforts implemented in order to improve the functioning of water management units (basins), there are still many difficulties facing authorities. It highlights the potential role of prices since they can change incentives, and their absence promotes overuse and encourages inequalities. It also acknowledges that infrastructure in the country is still deficient, especially in terms of irrigation infrastructure for agriculture. After explaining how authorities have tried to establish mechanisms to deal with water management problems, the paper concludes saying that water management problems in Mexico could be reduced through an integrated management system, where all stakeholders are given standing yet where social benefits prevail over individual interests.

22.1 Introduction

The interaction of biophysical, social, economic, and political factors make the management of water a complex and delicate task. Water is becoming scarcer in several areas of the planet, and the need for integrated water resource management

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between and within countries is more important than ever. Water conflicts are value-laden, and they cannot be resolved in a fully rational decision context. As Castelleti et al. (2008) suggest, “the combined presence of multiple water uses and strong vested interests in water resource management, both within and between nation states, requires the active involvement of the stakeholders in each stage of the decision-making process, from the identification of their preference structure to the negotiations of the decision(s) to be actually implemented.”

Water resources within a country may be managed numerous ways. Vargas et al. (2005) identify four general approaches:

1. *Project-oriented water resources*: In this case, priority is given to isolated projects like potable water, sewerage, irrigation, hydropower, recreation, etc. Benefits in this case are well identified, and the funding generally comes from the federal government.
2. *Subsector-oriented water resource development*: Planning at different government and users’ levels are generally present in these types of projects. Given that benefits have to be optimized for all stakeholders in the subsector, master plans are made in advance through negotiations.
3. *Subsector-oriented water resource management*: In this case, issues relative to water use are discussed and eventually solved through institutional innovation and infrastructure within well-defined subsectors. Projects are defined within an institutional framework and/or through a subsector analysis.
4. *Integrated water resource management*: The projects are the results of analysis processes that take into account all different water uses, including environmental conservation. Conflicts among users are resolved through increases in water supply, and through institutional innovation and demand control. Decisions are made at local or subsector levels, but taking into account other regional or national effects of these decisions. Dimensions of poverty, rural development, and increased productivity are also considered in this approach.

The first three categories of water management have been applied in Mexico at different times. While a number of policies have been implemented in endeavors that could be cataloged under the fourth category, we are still far away from a real integrated water resource management, as this work strives to illustrate.

The chapter is organized as follows. Section 22.2 describes Mexico’s water resources in terms of scarcity, inequality, and pollution. Section 22.3 explains how water resource management has changed in the country through time, and ends identifying the current management and its limitations. Section 22.4 describes international best practices related to water resource management. Section 22.5 enumerates the basic elements of an integrated water management system and reviews the status of the Mexican water management in relation to the optimum. A summary is provided in Sect. 22.6.

22.2 Water Resources in Mexico

In Mexico, the arid northwest and central regions contain 77 % of the population and generate almost 90 % of the total GDP. In contrast, poor southern regions have abundant water resources that are mostly used for hydropower and conservation purposes, given the lack of demand. The main use of water throughout Mexico is for agriculture (77 %). Another 14 % corresponds to public supply (which includes domestic and public uses); 4.1 % is supplied to industry, services and commerce; and 5.1 % is used in the thermoelectric industry (CONAGUA 2010).

Agriculture, livestock, forest exploitation, and fishing contribute 3.6 % of the gross domestic product (GDP) in Mexico, which is less than in 2003 (3.8 %). In Mexico, 21 million hectares are devoted to agriculture (around 10.5 % of the country's continental surface), with 6.5 million dependent upon irrigation (CONAGUA 2008). From a representative sample of irrigation production units, it is estimated that 46.2 % of this land uses the least efficient (less water-saving) irrigation technology—surface irrigation; 47.9 % employ sprinkler irrigation, and only 5.9 % uses the most efficient technology—drip irrigation (Ávila et al. 2008).

22.2.1 *Scarcity*

Water in Mexico is scarce. The shortage emerges partly from natural conditions, but it is deepened by several policy interventions. Moreover, these interventions sometimes cause consumers to impose further pressures on the availability of water. In rural areas, water is obtained both from superficial (63 %) and underground sources (37 %). Superficial sources are mainly recharged by rain water. It is important to mention that droughts affect mainly the north and the west parts of the country.

On average, annual availability of water per capita in Mexico is 4,288 m^3 (CONAGUA 2010), which is significantly lower than the average of 174 countries, which is equal to 17,650 m^3 (FAO AQUASTAT 2010). Moreover, Mexico's average has been constantly decreasing at a rate of 1.4 % per year (FAO AQUASTAT 2010).[1]

22.2.2 *Inequality*

Water in Mexico is both scarce and unequally distributed. As mentioned, significant supplies are allocated to irrigated agriculture, which relies heavily on inefficient technologies and contributes less than 4 % to Mexico's GDP. Regarding

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[1] Geometric average obtained from FAO's Aquastat data.

extraction of water for public use, in 2008 around 286 L of water was extracted per capita per day (CONAGUA 2008),[2] which is more than enough to fulfill daily requirements of water according to international standards of 150–170 L (World Health Organization—WHO). However, it is estimated that 44 % of this water is lost in the distribution process (Dávila et al. 2006). This fact implies that only 160 L are actually supplied. It is worth noting that even when the supply of water for public use seems sufficient, substantial regional variability exists. After accounting for estimated distribution losses, six of the 13 regions in Mexico (36 % of Mexican population) suffer insufficient supply of water to fulfill daily requirements. In short, natural availability of water is low, and the inefficient distribution system worsens the problem by leaving a large proportion of Mexican population without enough water to satisfy daily requirements.

Regarding technology, in Mexico there is a key factor that impedes the adoption of more efficient technologies: water for agriculture is heavily subsidized directly or indirectly. As an example, Ávila et al. (2006) suggest that if the subsidy on electricity consumption used for agriculture were eliminated, there would be savings of up to 35 % on water extracted from underground sources.[3]

Both empirically and theoretically, water market development seems important to increase productivity of water use. As an example, Yúnez-Naude and Rojas (2008) estimate that allowing water transfers at the northern region of the country would be beneficial to agriculture productivity. However, Mexican legislation must be reformed in order to take advantage of these potential benefits.

Regarding prices, water consumption at all levels is heavily subsidized. For example, the cost of managing and distributing water in Mexico City is around 10 and 11 pesos per cubic meter, but the price for the final consumer oscillates between two and three pesos per cubic meter. Furthermore, only 11 states recover their costs of water.

Water security is a necessary condition for human development (UNDP 2006), and it is directly related to the availability and distribution of the resource. The lack of access to water services is closely related to poverty conditions. Absolute poverty levels are closely related to the lack of access to public water infrastructure. Moreover, poor households suffer to a larger extent from interruptions of the service and have to assign a greater proportion of their income for water expenditures (Guevara et al. 2010).

This relationship between poverty and a lack of water is not casual, and we can distinguish two factors that help explain the link. First, public investment in water infrastructure is commonly allocated to municipalities with more political power and income. Second, isolation of population is important. In other words, it is costlier to provide water services to scarcely and dispersedly populated

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[2] CONAGUA states an extraction of 11.2 km^3. This number was divided by the population in December, 2008, as stated by the organization.

[3] Moreover, the authors show that this subsidy mainly benefits a reduced group of producers. While more than 68 thousand producers receive a subsidy of 20,000 pesos, 33 producers receive 500,000 pesos.

municipalities and to those located at higher altitudes. These are precisely the characteristics of marginal communities and municipalities. Finally, it should be noted that even though there is relatively high coverage of water services available in Mexico, a significant number of people do not have water security. This only accentuates inequalities within Mexico.

22.2.3 Pollution

Finally, important stocks and flows of water in Mexico are severely polluted. Wastewater is produced by domestic, industrial, and agricultural activities. However, the largest part of this pollution is related to domestic activities of the main three cities in the country: Mexico City, Monterrey, and Guadalajara. The main polluting industries in Mexico are sugar refineries and chemicals; efforts toward treatment of industrial sewage have not been enough to increase the volume of recycled water. Consequently, investment in waste treatment capacity has to increase to meet international standards.

The problems described suggest a clear need for improvements in water management, and the main purpose of this chapter is to discuss the areas in which governments can implement changes to optimize the use of this resource for present and future generations.

22.3 Recent Water Management Restructuring Process

Despite the current problems in terms of water scarcity, inequality of provision, overuse, and pollution, Mexico has a long and well-established tradition of water resources management (WRM), which started in the 1930s with large investments in storage capacity building and groundwater development to increase irrigated areas and to provide enough water for an increasing population. A law enacted in 1934 granted the federal government the powers to define sources and uses of water in the social property territory (rural community sectors, known as “ejidos”), while private land owners enjoyed a federally subsidized irrigation infrastructure and guaranteed market prices for their products. This situation eventually created two agricultural sectors in the country: a modern one with access to international markets and highly capitalized, and a lagged, precarious one, dependent on rainfall and with subsistence production levels. In 1946, a law for the preservation of water and soil was enacted.

It was not until the mid-1970s that the country adopted a National Water Plan, which identified the need to enact a new water law and to create a national water authority. The National Water Plan recognized the need for decentralization of the responsibilities regarding water management. However, it was not until the 1980s that the federal government created the National Water Commission, and the decentralization efforts started to be taken seriously, albeit in a top-down manner. At that time, municipalities were given relative autonomy and control over the management of potable water. In 1992 Mexico adopted the National Water Laws, which legally enabled the creation of water markets and led to the transference of irrigation district management to users' associations. The responsibility over surface and groundwater resources was given to the National Water Commission, reducing state governments' abilities to intervene on water issues (Donnell 2003). The National Waters Law of December 1992 represents the most important legal reform regarding water in Mexico. This law was reformed in 2004 and 2008. The new laws incorporated market forces in the water sector and converted water into a public good and a commodity, ended federal subsidies for water, and promoted basins as planning and management units (Donnell 2003).

In Mexico, there are 27 defined river basins covering the entirety of the national territory. These basins represent the most important water management authority unit. The choice to make basins the water decision-making unit was enacted in 1999, and supported due to the importance of managing this resource in accordance to the "natural flow of water" rather than on political limits. It is worth noting that this reform also allowed civil society to participate on an incipient water market, which was allowed to reduce subsidies from the government (Guerrero 2008). Inside each basin, authorities are responsible for integrating all water uses in the region; for considering the interactions among superficial and groundwater; for the provision of enough high-quality water for all users; for understanding the relationship among water and other natural resources of the basin; and, finally, for the optimization of use to promote economic and social development in the region. The existing basins are organized and administered by the National Water Commission through boards (councils) with federal, state, municipal, and major users' representatives. They provide representation for environmental uses of water.

As in other developing countries, water management in Mexico has been reorganized institutionally in favor of a decentralized, "integrated" structure (i.e., partitioned institutionally on a hydrographic basis rather than by types of users, such as agriculture, industry, and households). This is accompanied by the creation of water companies at a municipality level and oriented towards the reduction of demand within a framework of environmental regulation. However, several changes are still needed to reach a well-integrated water management system in Mexico. One of the main areas requiring change is in pricing practices.

According to OECD (2006) estimates, in 2001 a fee of 5 pesos needed to be charged in order to cover full capital and operational costs. However, each cubic meter was charged at a rate of 1.73 pesos at that time. Furthermore, water tariffs have been decreasing in real terms over time. Interestingly, a common empirical finding indicates that willingness to pay for water is greater than the tariff that would result if the subsidies were eliminated. For instance, Soto Montes de Oca and Bateman (2006) find that subsidies may be reduced up to 70 %, according to the willingness of the population in Mexico City to pay for water. Furthermore, subsidies are greater in the northern region of Mexico and in the federal district, which are the arid regions in which overexploitation is more severe. Economic efficiency aside, there is an issue of equity as cheaper water is available to regions with greater levels of development (Dinar et al. 2008).

Electricity used for water pumping is also subsidized when it is used for agriculture activities. This subsidy creates an artificial signal of abundance of water which causes overexploitation of aquifers. Additionally, this subsidy impedes the adoption of more efficient technologies and generates additional runoff and pollution. The subsidy to electricity for water pumping totals $1690 million pesos annually and mainly benefits a reduced number of producers (Ávila et al. 2008). These authors estimate that if the tariff was increased from 0.30 to 0.61 pesos, groundwater extractions would be reduced by 35 %.

Another area in which modernization is needed is infrastructure, although investment in this area has been extensive in the country. Decentralization of the water management system expanded public services to a large proportion of Mexicans, even though there are still a large number of inhabitants without access to a public water connection. Furthermore, these people are mainly located in rural areas, where poverty is pervasive. It is estimated that the federal budget for water infrastructure only covers 30 % of the required resources needed annually (Aregional 2006). Also, service quality is very low for that share of households considered poor. These households suffer from interruptions in service and from polluted water (Dinar et al. 2008).

General policy guidelines related to water are expressed in the National Water Program 2007–2012. This document describes eight general objectives intended to alleviate the main issues related to water. The eight objectives of the program are:

1. Improvement of water productivity in the agricultural sector.
2. Increased access and quality of drinking water, sewage and sanitation services.
3. Promotion of integrated, sustainable water management in river basins and aquifers.
4. Technical and administrative enhancement and financial development for the water sector.
5. Consolidation of the participation process of users and organized society in water management, and promotion of water culture for the proper use of this resource.
6. Prevention of risks related to meteorological and hydro meteorological events, and attention to their effects.
7. Assessment of the effects of climate change on the hydrological cycle.
8. Creation of a culture for paying duties and complying with the Law on National Waters in its administrative aspects.

In addition, the program considers research, technological development, and human resource training in the water sector as key factors to reach the proposed objectives. The program, as it is, in fact recognizes the major issues on the matter. In particular, the first four objectives are oriented to address the main problems described in previous sections. However, it is ambiguous as to the means in which each objective will be reached.

22.4 Best Practices in Water Management

The World Water Development Report 2009 (WWDR-3) states that a key factor to manage water resources effectively is to adopt an integrated approach. At the World Summit on Sustainable Development of 2002, countries agreed to develop integrated water management plans before 2005. However, it was recognized that this is a difficult task. In fact, only 24 % of the 104 participant countries have completed their plans (UNESCO 2009).

An integrated water management approach can be characterized by its core elements: water laws, water pricing mechanisms, river basin organizations, and international and intra-national agreements (Hooper 2006). An integrated view is important because isolated policies are proven to be less effective than a robust sustainable plan, which takes advantage of all the options available to improve efficiency of the water system. As an example, it is not wise to invest in increasing the number of water connections to households that experience a severe problem of water pollution or when interruptions in the system are very frequent.

It is claimed also that decentralization and participation of stakeholders is very important to improve the water management system. Including civil society and delegating responsibilities to lower levels of government may improve the management, as long as it reduces information asymmetries. UNESCO (2009) refers to evidence in South Africa where it has been observed that water management through scales smaller than river basins are ineffective. However, it is also recognized that this administrative approach, which is widely spread around the world, has not shown all the expected advantages to date.

Another important factor refers to coordination between public and private sectors as fragmented actions would lead to inefficiencies of the system. Other factors that are highlighted correspond to enhanced institutional arrangements, consultation with stakeholders, stimulation of public awareness about the problems with water resources, and promotion of research and development on the matter (UNESCO 2009). Hooper (2006) presents a summary of best practices regarding integrated water management systems derived from a review of more than 20 studies. Relative to decision-making processes, the author highlights the importance of consensus and coordination across sectors, the need for focusing decisions on efficiency terms, and to allow stakeholders to join in the decision-making process.

There are a number of other suggestions provided in Hooper (2006) that are important for water management. On the subject of financing, Hooper also finds that it is better to share costs, to assess ex-ante and ex-post management options, and to implement effective water pricing and alternative-demand management mechanisms. He finds advantages when the functions of the river basin organization are clearly specified in a national law. With regard to training, organizations have been successful in implementing programs to improve capacities and skills of their staff involved in water management. Finally, he stresses the importance of information and monitoring systems. These systems, he stresses, need to be accurate and up-to-date in order for them be helpful in the decision-making process.

From a more particular approach, the Human Development Report of 2006 highlights the importance of having a progressive collection system (pricing). A common practice is to implement block tariffs. However, this approach may have some disadvantages. For example, commonly the first block is set "too high," which reduces the power of discriminating users (Guevara et al. 2010; Boland and Whittington 2000). Another disadvantage is that this approach requires water to be metered, which is difficult in some places.

Another practice that has been useful in expanding water infrastructure where costs are very high is to adopt a participative approach. Empirically, it has been shown that poor households have a high willingness to pay for a water connection. Thus, one way to reduce costs of public investment is to ask the population to participate in the installation of public water connections. However, this practice is not feasible for very isolated households, since costs rise dramatically in those areas. In addition, this type of connection is prone to leakages and water losses, due to the lack of experience of people who install them.

In summary, the elements to be considered in the design and implementation of an integrated water management system (IWMS) are very diverse, and require scrupulous planning, monitoring, and corrective proceedings. In the following section, we describe the actions that have been taken to reach an IWMS in Mexico, and what is still pending.

22.5 An Integrated Water Management System for Mexico

A well-integrated water management system should at least have three actions: planning, monitoring, and correcting. These actions should be addressed at a national level and should consider the effects of decisions on all stakeholders involved. This section of the chapter will focus on the importance of each one of these actions to describe the interventions that are taking place in Mexico regarding each of them, and to give some recommendations about what should be done to improve them in the context of a unique water management system.

22.5.1 Planning

The National Water Plan 2007–2012 explicitly considers that sustainability is a necessary condition for economic development, and that water is a strategic resource. It also recognizes the importance of water management at the basin level, but talks about the importance of an integral water resource management vision. Integral management of water resources is a responsibility of basin authorities, and they are the starting point of the national water policy. These authorities are required to plan in order to optimize water use in terms of social welfare, economic development, and environmental sustainability. The National Water Plan is

Table 22.1 Estimated daily water supply per capita per day in liters

Number	Administrative region	Estimated daily water supply per capita per day (liters)[a]
I	Baja California	137
II	Northwest	582
III	North Pacific	248
IV	Balsas River	145
V	South Pacific	124
VI	Río Bravo	167
VII	North-central basins	137
VIII	Pacific-Lerma Santiago	152
IX	North Gulf	163
X	Central Gulf	119
XI	South Border	107
XII	Yucatan Peninsula	181
XIII	Mexico City Valley	152

[a] This estimation is the result of multiplying the volume of water for public use supplied by CONAGUA by 0.56, which is the estimated proportion which effectively arrives to its destination and dividing this product by the population of each region

a responsibility of the National Water Commission, and each one of the basin authorities are responsible for the specific water plans, the classification of water bodies, and the definition of water uses. The local subplans are integrated into the National Plan to reach an integrated water resource management (Table 22.1).

Among the most important planning activities regarding water in Mexico, we have:

- The establishment of natural protected areas where rainwater can be exploited to increase productivity of industrial and agricultural sectors dependent on rain-fed water.
- The establishment of protected drainage zones, to avoid contamination of natural protected areas.
- The definition of closed or rescued water areas.
- The definition of adequate water sources to generate hydropower.
- The expropriation of hydraulic public works or other types of installations when they can be exploited to increase productivity in the industrial and/or the agricultural sectors.
- The concession and elimination of permissions to private agents to exploit and use national groundwater or seawater.
- The elaboration of studies regarding new water sources, effects of overexploitation, new water uses, recycling technologies, and better management practices.
- The elaboration of studies regarding interactions between water and other natural resources, and biodiversity.
- The signature of international agreements regarding water in general.
- The establishment of irrigation districts and watershed/tech areas.
- The definition of legally binding norms regarding protection, improvement, and conservation of basins, aquifers, channels, and other water sources.

Despite the exhaustive list of planning activities, many of them face important implementation problems that have to be addressed by correctly designed incentive schemes for all stakeholders involved. On the other hand, each one of the basin authorities act as if they had no effects on other regions, which suggests real difficulties in water management in an integrated and coordinated way. Some suggestions to overcome these problems are related to the strengthening of the water federal authority by law, and the coordination with planning offices at the state and municipal government level. The planning time span in Mexico should be increased in a formal way to avoid real changes when parties alternate in power. Additionally, the thorough observance of the rule of law is necessary, as this is one of the most sensible points in the fulfillment of water planning.

22.5.2 Monitoring

In the context of an integrated water resource management, beyond planning and implementation of policies, the authorities need monitoring mechanisms to correct the course when either the quality or the quantity of water is deviating from optimum levels. This would help avoid economic losses and the problems that overuse or underuse of water causes in agricultural and industrial productivity, and to reduce the environmental effects of suboptimal water quality or quantity.

Monitoring actions are especially important for groundwater sources, given that they are the main providers of drinking water, and surface water availability is highly tied to them. Much of the flow in streams and the water in lakes and wetlands are sustained by the discharge of groundwater, particularly during periods of dry weather.

Groundwater systems are dynamic and adjust continually to short-term and long-term changes in climate, groundwater withdrawal, and land use. Water-level measurements from observation wells are the principal source of information about the hydrologic stresses acting on aquifers and how these stresses affect groundwater recharge, storage, and discharge. Long-term, systematic measurement of water levels provides essential data needed to evaluate changes in the resource over time, to develop groundwater models and forecast trends, and to design, implement, and monitor the effectiveness of groundwater management and protection programs.

Among the most important monitoring activities regarding water in Mexico, we have:

- Sampling of groundwater in most types of soil,
- Measurement of pore water pressure,
- In situ testing of hydraulic conductivity,
- Tracer testing for monitoring groundwater flow,
- Monitoring of the installation of meters or other measurement devices from authorized dealers,

- Checking the correct payment of water use, and
- Supervising the compliance of legally binding norms regarding protection, improvement, and conservation of basins, aquifers, channels, and other water sources.

Despite the laws and monitoring actions, 101 of 653 subterranean aquifers in Mexico are overexploited, the majority of them being located in the northern region of the country (Table 22.2). Moreover, a significant number of these aquifers are also negatively affected by saline intrusion. Given that 58 % of subterranean water is obtained from these aquifers, it is clear that monitoring actions have not been effective, and a radical change is also needed in this arena. It is worth noting that the number of overexploited aquifers grew from 32 in 1975 to 101 in 2008.

As we know, economic activity and population growth are inversely correlated with water availability from superficial sources, thus more pressures are imposed (and will be imposed) on subterranean sources as the country grows, which means that overexploitation of aquifers is likely to continue over time.

Table 22.2 Aquifer characteristics in Mexico by Region

Number	Region	Total	Number of aquifers			Average recharge (hm^3)
			Over-exploited	With marine intrusion	Affected by soil salinity and underground brackish water	
I	Baja California	87	8	9	5	1,258.9
II	Northwest	63	13	5	0	3,249.5
III	North Pacific	24	2	0	0	3,263
IV	Balsas	46	2	0	0	4,623.2
V	South Pacific	35	0	0	0	1,994.1
VI	Río Bravo	100	14	0	7	5,079.9
VII	Central Northern Basins	68	24	0	19	2,377.7
VIII	Lerma Santiago Pacífic	127	32	0	0	7,728.4
IX	North Gulf	40	2	0	0	1,316.4
X	Central Gulf	22	0	2	0	4,259.8
XI	South Border	23	0	0	0	1,8015.2
XII	Yucatán Peninsula	4	0	0	1	2,3315.7
XIII	México City Valley	14	4	0	0	2,339.8
	Total	653	101	16	32	80,821.6

Source CONAGUA (2010)

22.5.3 Corrective Actions

When planning and monitoring activities are not totally effective, due to political- or climate-related problems, governments at all levels should be capable of implementing corrective procedures to avoid deterioration of water quality or further reduction in water availability. Moreover, weather conditions like droughts or floods exert added pressures on water, and these problems have to be faced in an urgent fashion. In many cases, conflicts over water resources may create unrest as water resources become scarcer. These conflicts may take place between countries, between sub-national governments within countries, or between competing sectoral users or groups within countries. The situation is further complicated by the fact that a large proportion of major freshwater basins in the world fall within the jurisdiction of more than one nation or defined authority (Uitto and Duda 2002).

Corrective actions regarding water management are critical, because of the challenges generated when biophysical phenomena and human responses are linked but not completely understood. Furthermore, interactions between policy-making at different government levels and human-environment relations impose even more complications when interventions are needed in order to restore a basic equilibrium in water issues.

There are a number of corrective measures that can be taken by producers, consumers, and the government depending on the issue. Some corrective measures include:

- Crop substitution in dry lands,
- Crops and cattle insurance,
- Soil restoration and quality recovery,
- Reforestation,
- Investment in irrigation or in other kinds of infrastructure,
- Closure of at-risk aquifers and decommissioning of overexploited wells,
- Water use restrictions,
- Infrastructure maintenance and improvement of dams,
- Closure of fishing, exploitation and use activities in areas at risk,
- Relocation of populations at risk, and
- Land use changes.

We are aware that even the best water management system cannot prevent conflicts in water issues when eventualities occur, but we can learn from experiences of others on how to incur the least cost when these situations appear.

22.6 Conclusion

Water is the most important resource to safeguard the quality of life for humans and for economic activity. Mexico is among the five major mega-diverse nations of the world, and one of our major challenges is to achieve hydrological balance between surface and groundwater so as to meet the demand of all users, including ecosystems. In Mexico, natural availability of water is low, and the inefficient distribution worsens the problem by leaving a large proportion of Mexican population without the minimum water to fulfill daily requirements.

Preservation of water and the environment is a main goal in President Calderón's administration. Other central goals include the provision of adequate drinking water and sewerage services, installation of recycling systems, and the provision of enough water for agricultural and industrial activities. However, these goals have not been reached yet, and the climate complications expected in the near future impose the need to analyze water management options and to pursue actions in the shortest possible time.

To make sure available water is adequately preserved and used, policy interventions have to be designed in an integral framework. Despite the efforts of different authorities, water management in Mexico is still deficient. Our goal is to point out these deficiencies and to give some policy recommendations in order to improve the way water resources are administered in the country. This chapter has shown that Mexico has advanced dramatically in the last few years in terms of improving its water management; however, basic water problems that authorities have not been able to solve still exist. These problems have to be addressed in a more integral and coordinated way, involving not only authorities at the basin, municipality, and state levels, but also groups of users, and a national authority with a holistic view of the water problems the country faces.

One of the main areas where intervention is needed is pricing policies. Water is still highly subsidized in Mexico, albeit the National Water Law eliminated federal subsidies to this resource in 2004. Subsidies change incentives and promote overuse; moreover, price differences encourage inequalities, creating vicious circles among water availability, poverty, overuse, underinvestment, and low productivity.

Other areas where real efforts are required are related to infrastructure. Despite the strong investments of the last few years, the number of Mexicans that still lack access to potable water and sewerage services is unacceptable. Water provision for poor families is a time-consuming activity, and it is mostly performed by women and young people. This situation increases the probability of low educational levels, health problems, inequality, and poverty. Additionally, the low average productivity of the agricultural sector in Mexico is partly explained by the lack of irrigation infrastructure, especially in regions where weather is not suitable for crops highly valued in different markets. In Mexico, only 5.6 % of the agricultural land is equipped for irrigation; this means that 1,038,447 km^2 of the territory dedicated to agriculture (94.4 %), depend on weather conditions. Irrigated agriculture contributes about 50 % of the total value of agricultural production, and accounts for about 70 % of agricultural exports. Decisions regarding where to invest in terms of irrigation have to be taken at a federal level, considering costs and benefits for all the basins and regions, but ranking national welfare first.

Finally, a critical problem in terms of water in Mexico is pollution. As with other negative externalities, the private cost of polluted water is low, relative to the social cost. In this case, price discrimination and cash transfers are the ideal proposals to reduce the severity of the problem. However, water pollution involves information asymmetries that hinder the implementation of price solutions. An integral water management system has to deal, necessarily, with law observance, which means that participants other than the usual have to be inserted in the negotiation process.

International experiences can be a source of information for Mexican authorities in order to facilitate the implementation of policies that are correctly embodied in the laws but poorly enforced in practical terms.

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Chapter 23
Water Scarcity and Drought Management in the Ebro Basin

Miguel Ángel García-Vera and Rogelio Galván-Plaza

Abstract Water resources management practices fall under scrutiny when water scarcity problems become severe. This reevaluation occurs quite regularly in Spain because of the large temporal variation in the availability of water resources with frequent drought episodes. Present-day developments such as the growing environmental flow requirements or impending climate change further compromise the availability of resources for traditional water uses. The management of extreme events, such as droughts, requires that hydrological planning is based on management at the basin level, solid institutions, the best possible knowledge, public participation and co-responsibility in decision-making for all concerned stakeholders. This chapter presents the main strategies implemented in Spain, and in particular in the Ebro Basin, as an example of the decisions that need to be made during situations in which water is scarce.

23.1 Introduction

Spain is a territory covering half-million square kilometers with a population of 47 million inhabitants. At a general level, water management is carried out by different administrations. Urban supply is the responsibility of the local municipal councils, but if the supply covers various municipalities then it is managed at a higher level, such as states (called autonomous communities), the central government, or others. Water treatment and sewage is also the responsibility of local

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councils, but most states have collective water treatment systems installed. These are managed by states, so that the costs of investment, operation, and maintenance of infrastructures are carried out at a larger territorial level. Other responsibilities closely related to water, such as agriculture, the environment, and spatial planning are the responsibility of the central government in terms of basic legislation. However, the specific implementation of these policies is the competence of the states.

When a river basin extends beyond one state, the river basin authorities are part of the federal ministry of environment and have representatives of stakeholders in its governing bodies. The river basin authorities are in charge of hydrological planning, authorizations of surface water and groundwater extractions (water is a public good), water discharges, occupation of river banks, fines and penalties, control of water quality and quantity, flood and drought management, hydraulic projects and works of general interest, as well as the management of large-scale water systems. While the charges are quite similar, when the basins are solely contained within a single state, the river basin authorizes are part of the state government.

The river basin authorities in Spain have a long tradition dating back to 1926. They are governed by the principle of the unity of the basin (Confederación Hidrográfica del Ebro 2008). There are two types of river basin authorities, depending on the extension of the river basin over one or more than one state. River basins extending over more than one state are part of the Ministry of Environment (central government). There are nine river basin authorities of this type: Cantabrian, Miño-Sil, Duero, Tagus, Guadiana, Guadalquivir, Segura, Júcar, and Ebro basins. These basin authorities are called *Confederaciones Hidrográficas*. River basins contained entirely within a single state are part of the state government, and these basins are Basque Country, Galicia Costa, Guadalete-Barbate, Tinto-Piedras-Odiel, Andalusia Mediterranean Coast, Catalonia, Balearic Islands, and Canary Islands.

Basin authorities are governed by collegiate bodies, which are responsible for water planning and management within an organization built for participative decision-making by stakeholders. These bodies are the governing board, and the management, participation, and cooperation bodies.

The governing board includes representatives from public authorities and water users, and its main role is the approval of the budget. The management entities are the assembly of users, the withdrawal committee, and the watershed boards. The assembly of users is made up of representatives of water users, and coordinates the operation of hydraulic works and water resources throughout the basin. The withdrawal committee makes decisions on water storage (e.g., filling or emptying reservoirs and aquifers in the basin). The watershed boards are composed of representatives of users and the basin authority, and coordinate the operation of the hydraulic works and water resources in local watersheds inside the basin. The Ebro basin has 17 watershed boards.

The participation body is the water council, which spreads information, makes public consultations, and participates actively in hydrological planning. Its members are representatives from water users, and from government and non-government organizations. The main task is to approve the hydrological plan of the basin. The cooperation body is the committee of competent authorities, with representatives from the different federal, state and local governments. Its main task is to guarantee cooperation among public agencies in the application of regulations for water protection.

The water user associations are also important institutions dealing with water management at the local level. They are made up of users of the same water abstraction or concession, and they are public law entities ancillary to the basin authority. Their main tasks are water management at the local level, and enforcement of water rules and regulations. In the Ebro Basin, there are nearly 2,000 water-user associations, most of them for irrigation purposes.

23.2 Reponses and Adaptations to Droughts

The strong temporal variability of precipitation in Spain results in quite frequent drought spells, which could persist up to several years. Water resources availability and consumption by basin are presented in Table 23.1. The basins with higher consumption relative to availability are those in southern and eastern Spain, particularly Segura. As shown with respect to Segura as well as number of other basins, consumption often exceeds minimum flows. The unbalance can sometimes be covered by water transfers, as is the case of Segura in which large water transfer come from the Tagus basins. Additional supplies may now also come from desalination given the recent expansion in this area.

More recent calculations of resource availability have been estimated with data series covering the period 1980–2005. The results indicate that water resources are between 15 and 20 % below those of Table 23.1. In addition, a high variability of precipitation is detected in this period, leading to drought spells in basins that did not have problems previously. This has occurred, for example, in the urban supply to several major cities in northern Spain, which is an area traditionally wet and lacking infrastructures to cope with drought situations.

23.2.1 Basin Hydrological Plans 2010–2015

Proper management of shortages and droughts requires prior hydrological planning in order to provide a foundation for sound decision-making. The hydrological plans now in force in the Spanish basin authorities were approved in 1998 (Confederación Hidrográfica del Ebro 1996; Boletín Oficial del Estado 1999). Basins are currently undergoing a planning process that faces a number of major challenges, with the implementation of the European Water Framework Directive (Diario Oficial de las Comunidades Europeas 2000; Boletín Oficial del Estado

Table 23.1 Available resources, demand and reservoir storage by river basin in Spain

Planning district	Surface area (km^2)	Annual river flow (Mm^3/y)		Reservoir capacity (Mm^3)	Urban, industrial, irrigation demand (Mm^3/y)	Consumption (Mm^3/y)
		Minimum	Average			
North I	17,600	5,602	12,689	3,040	584	403
North II	17,330	6,286	13,881	559	549	145
North III	5,720	2,195	5,337	122	486	98
Douro	78,960	4,926	13,660	7,654	3,827	2,929
Tagus	55,810	2,475	10,883	11,131	2,668	1,728
Guadiana I	53,180	260	4,414	8,508	2,307	1,756
Guadiana II	7,030	46	1,061	684	219	121
Guadalquivir	63,240	436	8,601	8,208	3,760	2,636
South	17,950	122	2,351	1,160	1,350	912
Segura	19,120	294	803	1,144	1,834	1,350
Júcar	42,900	1,564	3,432	3,343	2,927	1,958
Ebro	85,560	8,815	17,967	6,761	7,038	5,361
Catalonia I.B.	16,490	912	2,787	692	1,349	493
Galicia Coast	13,130	5,360	12,250	688	795	479
Balearic Islands	5,010	175	661	11	288	171
Canary Islands	7,440	37	409	101	427	244
Spain	*506,470*	*50,390*	*111,186*	*53,806*	*30,408*	*20,783*

Source Ministerio de Medio Ambiente (2003). Data series for the period 1940/1995

2003). The objectives of hydrological planning are to achieve good ecological status of water bodies while meeting water demands for regional and sector development, increasing the availability of resources, protecting water quality, economizing water use and making allocations that are consistent with environmental flows that support ecosystems.

The new basin hydrological plans are being completed for the period 2010–2015. These plans have to be endorsed by the water council of each basin before being finally approved by the Spanish government. The program of measures of the Ebro Basin plan is presented in Table 23.2.

The measure with the largest investment is modernization of irrigation systems (30 %), which includes changing flood irrigation to drip and sprinkler systems, and building water storage facilities. Other important measures are new irrigation developments (28 %), water and sewage treatment (10 %), and water supply projects (7 %).

The feasibility of new irrigation developments should comply with several conditions defined by the Ministry of Environment (Boletín Oficial del Estado 2008a), which ensures that irrigation demand could be satisfied with available

Table 23.2 Program of measures in the updated Ebro basin plan

Budget by objective and measure	Million Euros	Percentage
Objective A: environment		
A1. Water and sewage treatment	492	10.2
A2. Environmental restoration of rivers and river banks	45	0.94
A4. Restoration of areas affected by dumping	17	0.36
A5. Plan for the re-use of urban and irrigation effluents	4	0.09
A6. Agro-environmental measures in irrigation	42	0.88
A7. Protection of groundwater	20	0.42
A8. Modernisation of irrigation	1,433	29.89
A9. Implementation of ecologically-friendly flows	18	0.38
A11. Control networks	24	0.5
A13. Supply plans	323	6.73
A14. Protection of the Ebro Delta	85	1.76
A15. Emergency plan for allochthonous species	57	1.18
A16. Treatment of contaminated sediments	87	1.82
A18. River continuity improvement plan	6	0.12
A22. R&D	14	0.29
Total objective A	*2,750*	*57.3*
Objective B: demand fulfillment		
B1. New irrigation	1,338	27.9
B2. Reservoirs	210	4.37
B3. Energy uses	9	0.18
B5. Recreational and leisure uses	43	0.89
B7. Plan for the preservation, maintenance and security of hydraulic infrastructure	16	0.34
Total objective B	*1,627*	*33.9*
Objective C: extreme phenomena		
C1. Drought plans	44	0.92
C3. Maintenance of a monitoring system for river flooding	39	0.8
C4. Mapping of zones liable to flooding	12	0.26
C5. Cleaning and maintenance of river banks	217	4.53
C10. Infrastructures for controlling flooding	88	1.83
Total objective C	*422*	*8.8*
Total measures in the Ebro basin plan	*4,800*	*100*

resources. These conditions state that irrigation projects are not feasible when the shortage of water in one year is below 50 % of demand, or the sum of deficits in two consecutive years are below 75 % of annual demand, or the sum of deficits in 10 consecutive years is below annual demand. The usual level of guarantee in new irrigation projects is 80 %, and these new projects have to comply with the conditions of the environment impact assessment studies.

23.2.2 The Drought Plans

Droughts have special consideration in hydrological planning. There have been many droughts in the Ebro Basin. In 1949, a major drought affected the whole Ebro Basin with the lowest inflows ever recorded. During the 1988–1995 period, the Cantabrian and Pyrenees areas experienced one of the most severe droughts ever recorded. The 1993–1995 drought in the Jalón Basin led to major disputes between the irrigators as they had to face water restrictions. The drought of 1998–2000 involved the right-hand tributaries from the River Iregua to Matarraña. The droughts of 2001–2002 and 2004–2005 affected the rivers of the central Pyrenees and water supplies to one of the main towns in the basin, Huesca, which was solved with an emergency connection with an irrigation channel.

The drought of 1990–1995 was detected when it was already in a fully advanced state. This meant that only emergency measures could be adopted. These measures did resolve specific problems, but not in a planned manner. This experience demonstrated the need for drought management. The response was the design of a system to detect droughts using indicators that could activate specific operating regulations or action plans devised in advance as a response.

This proposal was included in the National Hydrological Plan of 2001 (Boletín Oficial del Estado 2001), which called for preparation of drought plans in each basin. These plans have to include an overall system of hydrological indicators for droughts, action plans, and emergency plans for urban centers. The action plans would be applied during droughts to specify the rules for operating systems and the measures to be applied. The emergency plans would cover all water-supplying systems in urban centers serving populations above 20,000 inhabitants.

Under the law of the National Hydrological Plan of 2001, the federal government and the governing boards of the basin authorities have the power to adopt extraordinary measures during droughts, such as limiting water rights and carrying out emergency actions with extraordinary state resources (Boletín Oficial del Estado 2001). Emergency decrees have been passed since 2001 during periods of severe drought to mitigate their adverse effects (Boletín Oficial del Estado 2008b, c).

The drought plan (Confederación Hidrográfica del Ebro 2007) include a thorough analysis of the meteorological droughts through a detailed analysis of the precipitation series for the basin, and of the hydrological drought through the historical analysis of available data on river flows since 1913, piezometric levels of groundwater with data since 1989, and the water accumulated in the form of snow with data since 1986. This analysis has allowed a characterization of the dry periods 1948–1950, 1956–1959, 1988–1989, 1995–1996, and 2001–2002. The most severe in terms of intensity was 1948–1950, and in terms of duration that of 1988–1996. The drought during 2001–2002 is also remarkable for the lack of precipitation and inflows. The management measures applied in each of the previous droughts were compiled and analyzed.

The drought plan divides the basin into sectors with similar hydrological behavior during drought spells. Each sector has drought indicators based on the storage of reservoirs, river flows, snow accumulation, piezometric levels, and wetland levels. These indicators define the state of the basin at any time with respect to drought, identifying normal, pre-alert, alert and emergency situations. The indices are calculated monthly and the stakeholders in the basin are informed accordingly on the drought situation.[1] Based on these indicators, the drought plan applies the protocol of measures for each operating system and drought conditions. A summary of these measures is presented in Table 23.3.

The definition of indicators, their thresholds and the drought measures has been completed through a technical process managed by the water basin authority. Throughout the process, stakeholders have participated through their respective water councils and society at large has participated through public information campaigns between November 2006 and January 2007.

The emergency plans are being drawn up for towns of more than 20,000 inhabitants. At present, the plan for the Pamplona area within the Ebro Basin has been approved (325,000 inhabitants), while the plan for the Bilbao Bizcaia Water Consortium (800,000 inhabitants outside the basin) is awaiting approval. Other large systems of urban supply, such as Madrid, have had emergency plans for a number of years.

The emergency plans define the measures to be adopted in each phase of the drought. Preventive measures identify the conditions under which drought phases start, and full drought measures deal with the management and operation of urban supply systems. Institutional measures interact with the agents responsible for providing resources, legal, and regulatory actions, and special measures to address environmental impact. Other measures deal with the implementation, expansion or improvement of water provision facilities. Finally there are also measures to monitor the drought situation and risks.

23.2.3 Example of Measures Applied During the Last Drought in the Ebro Basin

In the 2004–2005 drought, drinking water was supplied by cisterns to 60 municipal areas of under 1,000 inhabitants. The city of Huesca (50,000 inhabitants) had restrictions until an alternative supply entered into service in August 2005 from the Cinca reservoir.

In terms of irrigated agriculture, approximately 70,000 farmers changed their crop plans to use less water by reducing the acreage of corn (−30 %) and rice

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[1] See these indicators at the following links: http://www.mma.es/portal/secciones/aguas_continent_zonas_asoc/ons/mapa_informe_ons/informes_cuenca.htm and http://oph.chebro.es/DOCUMENTACION/Sequia/IndiceMes.pdf.

Table 23.3 Summary of the main measures of the Ebro basin drought plan

Situation	Measure
Pre-alert	Detailed monitoring of the situation
	Drawing up forecasts
	Estimate distribution of crops
	Raising awareness of the need for saving
	Information to users
Alert	Creation of the permanent drought commission
	Verification of the activation of the urban supply emergency plans
	Increase control and vigilance of compliance with measures
	Intensification of campaigns for savings in urban supply
	Reduction of supplies for public uses (watering in parks, etc.)
	Reduction of agricultural allocations of up to 10 %, with priority for woody crops
	Start-up existing drought facilities
	Correction of losses in supply networks
	Monitoring and evaluation of environmental flows
	Activation of the centre for exchange of concessionary rights (does not exist yet)
	Increased monitoring of indicators of quality and the ecological state of waters
	Control and vigilance of abstractions and concessionary conditions
	Drought reductions in large irrigation areas, by proportional division of available water between users
	Information to the states governments so that they can respond
Emergency	Appeal to the federal government to enact a drought decree
	Check the activation of the emergency urban supply plans
	In urban centers without emergency plans, imposition of water saving measures
	Daily cuts of water supply during certain times of day
	Reduction in irrigation consumption, trying to ensure the survival of woody crops
	Check that the reserve storage in dams for urban supply is maintained
	Transfer of rights between users (not created yet)
	Gradual adaptation of the environmental flows to flows in the natural regime
	More controls on water discharges, agricultural returns, and quality and environmental indicators
	Plans for using new alternative resources
	Promotion of the emergency re-use of waste water for irrigation
	Stricter control of water abstractions
	Launch of information campaigns and weekly publication of information on the state of the drought

(−20 %), while another 314,000 farmers received a reduced allocation of water. Consequently, irrigated acreage decreased by 10 % and production incurred losses of 540 million Euros. Hydroelectric production fell by one-half, which generated losses of 98 million Euros. There were increasing sporadic and scattered discharges that caused a deterioration of water quality, with frequent mortality of fish in some river stretches. The environmental river flows were not fulfilled in a large number of control stations. For example, during March 2005, 64 of the 101 control stations were not complying with the environmental flow requirements.

The main measures taken during this drought were providing alternative urban supply sources for Huesca and for the towns of Pallars Jussá, Segarra and other isolated towns in the Pyrenees mountains. Other measures were test drills throughout the Ebro Basin to detect new aquifers, construction and studies of wells in Hoya de Huesca and around Morella, emergency pumping to prevent loss of plantations in the Aragon and Catalonia canal, the repair of the Lodosa canal, and the refurbishment of the canal feeding the González-Lacasa reservoir.

There were also management measures such as proportional reduction in irrigation allocations by the watershed boards, withdrawal of land and change in crop cultivation, and control of water storage in reservoirs by the withdrawal commission. Another management measure was to coordinate the operation of dams in order to supply the water systems with the greatest shortfalls. For example, the Itoiz reservoir was used to supply environmental flows to the lower Aragon River, or the Noguera Ribagorzana River resources were assigned with more flexibility to mitigate the drought in the Aragon and Catalonia canal.

Other historical actions taken in previous droughts in the Ebro Basin are worth highlighting. One was to acquire additional supply sources for Bilbao (850,000 inhabitants) and Vitoria (250,000 inhabitants) in the 1990 drought, by building emergency collection, pumping and conduction facilities. All these facilities are currently operational as backup sources to cope with emergency situations in the future. Many urban supply systems in the Ebro Basin are being improved with new abstraction sources to prevent drought problems. These new sources have greater reliability and better quality, and are supplying water to Lerida (120,000 inhabitants), Zaragoza (640,000), Pamplona, (192,000) and Logroño (142,000).

Another case between 1995 and 1998 was the provision of supplementary resources from the River Jalón and the Tranquera reservoir. A conduction and a pumping station were built to transfer water from the River Jalón to the Tranquera reservoir in the River Piedra. However, the facility has never been operational because farmers are not willing to cover the operating and maintenance costs. This scarcity problem derives from the increase in private irrigation using groundwater in recent decades, leading to greater vulnerability of the system to droughts and resulting in a very serious social conflict during the 1995 drought. To solve the problem, the basin authority decided to limit granting of new groundwater concessions on a temporary basis, to implement rigorous inspections on the legality of all concessions, to control groundwater and surface extractions, and to complete a hydro-geological study to improve the management regime of the aquifers in the middle Jalón basin. In addition, two new reservoirs are being built (Lechago and Mularroya) and there are important projects to modernize the irrigation schemes in the basin.

Another action taken between 1995 and 1998 was the provision of additional resources to the Pena reservoir, by pumping water from the River Matarraña to a reservoir located in one of its tributaries. However, this measure has not been implemented since 2000 because of the strong social opposition to it. The alternative has been to build several storage reservoirs to improve the reliability of water use in the Matarraña watershed.

There was an emergency pumping of water from the Santa Ana reservoir to the Aragon and Catalonia canal in 2005–2006. This action is currently in operation and has been disputed by irrigators downstream who consider that these extractions jeopardize their concessional rights.

There have been many test drills, well construction and hydro-geological studies for cases of emergency water provision. Since 1995, there have been 60 test drills and most of them have been in operation. The rest has not been in operation because users consider too expansive the operating and maintenance costs (Tierga wells).

Other drought mitigation policies have been taken at the national level. One important policy is seawater desalination. The AGUA project was approved in 2005 to build desalination plants in the Mediterranean coast with investments of 5 billion Euros and a desalination capacity of 600 Mm^3 per year. At present there are some 700 desalination plants in Spain with a capacity of 672 Mm^3 per year.

The water transfers among basins are another policy option that has been considered in Spain. The main interbasin transfer in Spain is the Tagus-Segura transfer, conveying water from the Tagus to the Júcar, Segura, and Sur basins. Transfers are decided by the Spanish government during drought spells, and they always generate heated disputes and tensions between stakeholders. In the 1990s there was a project to interconnect all major basins in Spain by moving 4,000 Mm^3 of water, but the project collapsed because of the huge size of the investment and the political disputes among territories and groups of interest. Another large interbasin transfer was decided in 2000 from the Ebro Basin to the Jucar, Segura and South basins, but the resulting conflicts among regions, political parties and groups of interest led to the collapse of the project.

Other drought policies at the federal level are the promotion of agricultural insurance against droughts and the real-time monitoring of flows, reservoir levels, precipitation and piezometric levels. This monitoring comes from the automatic hydrological information systems (SAIH) operating in each basin authority,[2] and contributes to the early detection and management of droughts.

An important lesson from these drought policies and measures is that when water is abundant and there is not much pressure on resources, water management is mostly a local matter. However, when scarcity becomes severe or when a strong drought spell occurs, then the integrated management of resources is crucial. This integrated management combines the basin authorities with strengthened stakeholder participation in the decision-making process at basin scale. This cooperation builds the collective action required for a sound decision-making in order to cope with the difficulties arising from severe droughts and scarcity events.

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[2] This information is publicly available at http://195.55.247.237/saihebro/.

23.3 Other Possible Responses and Adaptations

The experience acquired in Spain in dealing with droughts reveals several strategies to endure severe drought spells, with examples of success and failure. One strategy is to expand water supply with new dams, desalination facilities in coastal areas, interbasin transfers, and conjoint management of surface water and groundwater. These supply projects may involve large investments and should be analyzed regarding their economic feasibility, social acceptability, and environmental implications; failure to do so may result in unnecessary outcomes that could lead to their collapse if ignored and not considered.

As indicated above, interbasin water transfers are a recurrent issue in Spain that has involved intense debate and confrontation among territories, political parties, and groups of interest. The latest interbasin transfer proposal was made in the spring of 2008 during an acute drought in the Catalonia Basin. At the time, the urban supply to Barcelona was being supplemented with water carried by ships from Marseille in France and Tarragona. The water transfer proposal was to take water from the Segre, a tributary to the Ebro River, or directly from an existing aqueduct in the lower Ebro. The debate was quite strong and the transfer was approved by the federal government, but then the drought ended abruptly when heavy rains started over the region. Since the emergency situation was resolved, the approval of the water transfer was repealed. The entry in operation of several desalination plants on the Catalan coast indicates that water transfers will not be an issue in the future.

Another water transfer proposal that generated a major social debate was the Ebro water transfer to southeastern Spain, moving 1,050 Mm^3 per year from the lower Ebro to the Mediterranean coast up to Almeria, with an investment close to 6 billion Euros. This major facility was not built because of the change of leadership in the federal government after the elections in 2004.

A different type of strategy is to control water demand. In Spain this involves the reallocation of irrigation water that accounts for 80 % of the demand for water. Over the last decade, the National Irrigation Plan has been a major effort involving both public and private financing to modernize irrigation systems and operations with large investments of up to 6 billion Euros in advanced technologies. Modernization improves land profitability and the working conditions of farmers, and reduces the pollution loads released into streams and rivers. It reduces also the water imbalances in irrigation districts because of the efficiency gains in irrigation systems, and lessens the vulnerability to drought. The investments in modernization are expected to continue with a second irrigation plan being prepared.

Some strategies focus on management measures such as exchange centers of water rights, control of water extractions, and water pricing. The exchange centers of water rights were introduced in the water law in 1999 to facilitate the transfer of water rights between users under certain conditions. The exchange centers are created by the federal government at the request of the river basin authorities. Basin authorities bid publicly for the acquisition of water rights, which are transferred to other users willing to pay for them. At present, there are exchange centers in the Júcar, Segura, Guadiana, and Guadalquivir basins, but water transactions have been very low.

Most of the water trade activity has taken place in the Guadiana basin, within the Special Plan for the Upper Guadiana (Boletín Oficial del Estado 2008d). This plan tries to recover the large Western La Mancha aquifer with investments amounting to 3 billion Euros, including almost 1 billion Euros to purchase 70,000 ha of water rights by the basin authority. However, the water authority has spent only 30 million Euros in the last 3 years to purchase the water rights of 1,600 ha. The possibility of further acquisitions is dim because of the current financial austerity in Spain.

The control of extractions by basin authorities is a high priority of the federal government, with approved regulation (Boletín Oficial del Estado 2009a, b) forcing all concessionaries to install measuring devices. The modification of the water law in 1999 already required the installation of measuring devices. This measure would improve water use efficiency and release water resources to comply with environmental flows. At present this regulation is being implemented only in some pilot areas, but compliance is going to be problematic even with financial incentives for installation and monitoring.

Water pricing is a core policy of the European Water Framework Directive (Diario Oficial de las Comunidades Europeas 2000) to implement the cost-recovery principle of the directive. Since the beginning of the elaboration of the directive, there has been an intense debate about this principle, and Ireland forced to change the directive from “full cost recovery” to “close to full cost recovery.” Water costs in Spain differ according to the entity providing the service because of the specific facility investments involved. In the case of urban supplies, each local council or group of councils has its own way of costing. For water treatment, it may depend solely on the local entity or on the state government. For local entities, the cost recovery depends on the financial arrangement that is decided at the time of building the water treatment system. For states, the cost recovery is defined through a payment called water treatment fee.

The basin authorities have an impact on costs through several fees and tariffs defined by law. Two more important components are the regulation fee and the water use tariff (Article 114 of Boletín Oficial del Estado 2001). The investment and maintenance costs of reservoirs and canals built with federal funding are met by their users for a period between 25 and 50 years. At present, there are no plans for water pricing as a tool to improve water use efficiency. In recent years, this efficiency issue has been addressed through conditions placed on the investments funded by the European Union, and also through advertising campaigns to improve urban water savings. In fact, some cities such as Zaragoza with increasing populations over recent years have managed to reduce water use from 90 down to 60 Mm^3 through network investments and public water saving campaigns. Throughout Spain, domestic consumption has fallen to only 96 L per person and day (Comisión de las Comunidades Europeas 2007). It should be noted that with respect to the agricultural sector, water fees and tariffs for irrigation may be waived given that the income of farmers is less than in other sectors of the economy.

One of the main objectives in the new hydrologic plans being approved is the definition of minimum ecological flows, enforced at the main points of the basin control network. The methodology to establish these flows is outlined by the federal ministry (Boletín Oficial del Estado 2008a), and the technical studies for implementation are being completed at present. The minimum ecological flows have to be compatible with the objective of the Water Framework Directive calling for the good ecological status of water bodies. The drought spells should be considered also in the estimation of these ecological flows. Nevertheless, there is a lack of knowledge and experience on the impact of flows over the ecological status of water bodies. Therefore, the implementation of ecological flows has to be made with prudence to avoid unnecessary negative impacts on current and future water users.

23.4 Recommendations for Future Developments and Research Needs

There is a growing concern over water scarcity and droughts in the European Union. In 2007 the European commission presented a “Communication” addressing the challenge of water scarcity and droughts in the European Union (Comisión de las Comunidades Europeas 2007). The global concern regarding droughts has spurred the design of important R&D strategies by a large number of institutions. In Spain, the federal ministry of environment established a national drought observatory in 2005 to coordinate all administrations dealing with water resources. The observatory is a center for knowledge, forecast, mitigation, and monitoring of droughts across the country. It provides information on hydrology and monitoring reports on droughts prepared every month, legislative and management measures implemented by state and local governments in Spain, and information on environmental education.[3] The activity of the observatory increases significantly during drought spells, and the observatory focuses on research activities related to droughts (Ministerio de Medio Ambiente 2007). The European Parliament requested the creation of a European drought observatory in 2009. This initiative has been joined by the European EUROGEOSS (www.eurogeoss.eu) project which has the objective of developing a European drought observatory within the framework of the INSPIRE specifications and Group on Earth Observations (GEOSS) interoperability arrangements. This observatory will be fully integrated with local and national systems in Europe and international drought early warning systems, such as the global drought early warning system.

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[3] The link to the web page of the observatory is www.marm.gob.es/es/agua/temas/observatorio-nacional-de-la-sequia/.

Defining new lines of research on drought involves studying the relationships between climate change and droughts. This is an important subject in the Spanish National Plan for Adaptation to Climate Change, focusing on the evaluation of the climate change impacts on the frequency and duration of droughts. The research makes use of simulation models of precipitation and inflows under different climatic scenarios. The effects of climate change are being analyzed by looking at water demand (specifically in agriculture), the behavior of water systems under several new scenarios, and the impact on ecosystems and biodiversity in both inland and coastal areas.

A research field with high priority in Spain is drought prediction. The geographical location of Spain makes drought predictions difficult by using climatic indicators. Some researchers have agreed on studying the relationships between some climatic indicators (North Atlantic Oscillation-NAO) and droughts in Europe (Vázquez López 2004; López-Moreno and Vicente-Serrano 2008). Another initiative is the creation of banks of good practices, such as the European Union water scarcity group document (Water Scarcity Group 2005), which suggests collecting good practices for understanding effective measures and transferring appropriate technologies between countries. The Mediterranean drought preparedness and mitigation planning (MEDROPLAN) project has issued a collection of guidelines for the management of droughts.[4]

The effort requires investments in research and application of the best technologies and management skills to ensure optimal efficiency of water systems. The aim is to promote advanced research on adaptation of the economic activities to water scarcity and drought, on water-efficient technologies and on the improvement of public and private decision-making. A good example is the progress in deficit irrigation techniques resulting in less water consumption of crops.

Other research initiatives focus on obtaining new water resources from desalination, supplementary water supply from groundwater in emergency situations, artificial recharge of aquifers, and water reuse and regeneration. This is the case of research projects such as membrane-based desalination: an integrated approach (MEDINA) and desalination of seawater through an innovative solar-powered membrane distillation system (MEDESOL) to reduce energy consumption in desalination and brackish water discharges.

23.5 Conclusions

Water scarcity and droughts are becoming problems of concern in the European Union. Droughts have always been common events in Mediterranean countries, and Spain has considerable experience and interest in the subject. In recent years, there has been major progress in the planning process for droughts in Spain, and

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[4] Available on the link www.iamz.ciheam.org/medroplan/guidelines/index_main_page.html.

drought plans for every basin have been elaborated and approved in 2007. This planning effort contributed to reduced damages in the last drought between 2005 and 2008. The drafting of these plans, together with the forthcoming basin plans of 2010–2015, provide a good foundation for managing water scarcity in Spain.

The main challenges for the management of water resources in Spain are related to the current and future investments in irrigation and seawater desalination, the determination of ecological flows in rivers and streams and their enforcement, the control of water extractions to avoid further water scarcity in basins, and the new thrust to invigorate the centers for water rights exchange. Water management in Spain is organized by hydrological basin and with stakeholders inside the basin authorities participating in decision-making and enforcement. These institutional features are quite important to solve the problems of water scarcity and droughts, and to move towards a more sustainable management of water resources in Spain.

The future lines of research and development should address the impacts of climate change and droughts on human activities and ecosystems, the prediction of droughts and their management, the creation of banks of good practices, the spread of scientific and technical knowledge on water efficiency and its application by improving water systems, the development of new water sources such as desalination, artificial aquifer recharge, and reuse and regeneration of wastewater.

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Chapter 24
Responding to Extreme Drought in the Murray-Darling Basin, Australia

Murray-Darling Basin Authority/David Dreverman

Abstract Over the first decade of the twenty-first century, the Murray-Darling Basin experienced the most severe drought in recorded hydrologic history. Inflows into some rivers of the Murray-Darling Basin in 2006, particularly the Murray, whose waters are shared by three states, were at record low levels. Special water-sharing arrangements were developed for approval by first ministers of relevant governments. Inflows in 2007, 2008 and into 2009 required extensive adaptation of dry inflow contingency planning to ensure that critical human water needs could be met in successive years. This chapter reviews the lessons learned in implementing a comprehensive response to critical water shortage over 3 years of extreme drought.

24.1 The Murray-Darling Basin

The Murray-Darling is Australia's largest river system—the Darling is the longest river in Australia, extending 2,740 km, and the Murray is 2,530 km from its source to its mouth. It is one of the world's major river systems, ranking 15th in terms of length and 21st in catchment area. It has a very low mean annual discharge, compared to other major river systems, and flows are extremely variable. With a catchment area of more than 1,060,000 km^2, it covers approximately 14 % of Australia and is part of five of the eight states and territories in Australia.

This river system is vital to the Australian economy. It has been called Australia's agricultural heartland, the nation's "food basket." The area of commercial agriculture on farms and other enterprises in the basin covers 88.6 million hectares, 19 % of the Australian total (2000/2001) (Murray-Darling Basin Commission website; Crabb 1997). The area of irrigated agriculture in the basin is more

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than 1.9 million hectares, 75 % of the Australian total, with a gross value of agricultural production estimated at $13.6 billion in 2000–2001, 40 % of the Australian total (2000/2001). It supplies water to 2 million people within the basin area and is the major source of water to 1.1 million people living in Adelaide, the capital of South Australia, located outside of the basin.

The basin contains areas with extremely high cultural heritage value to the Australian Aborigines. As it was a source of permanent water in an arid continent, Aboriginal communities have lived along the rivers for 40,000 years. The basin has a range of ecosystems from wide infrequently flooded floodplains in arid areas to permanent wetland areas. Many of the areas are unique to Australia and the world. Most of the Australian iconic flora and fauna species can be found in the basin. It contains many of the 49 wetland systems in Australia that have been recognized as being of international significance and are listed under the 1971 Convention of Wetlands of International Importance (the Ramsar Convention). The area is also subject to international migratory bird agreements with both Japan and China.

Australia is very much a land of "drought and flooding rains," with high variability in rainfall and inflows to rivers. As a general rule, it would be considered to be relatively dry.

The Murray-Darling Basin has the following characteristics:

- average rainfall of 480 mm/year
- average run-off of 23,850 GL/year
- average inter-basin transfers of 1,200 GL/year
- Water use in the basin averages:
    - surface water 11,500 GL
    - ground water 1,400 GL
- TOTAL water use of 12,900 GL

However, surface water use was only 4,500 GL in 2007–2008 and 4,130 GL in 2008–2009. Demonstrating the variability of water availability in the basin, the use in 2007–2008 was, at the time, the lowest in 25 years since basin-wide records have been kept, but it included 1,054 GL of use in the northern state of Queensland, which is the highest ever use in that state.

24.2 Water Planning and Annual Allocation

Prior to 2006, the Federation Drought (1895–1903) represented the most severe prolonged dry sequence in the historic record, which dated to 1892. Water resource planning in the Murray-Darling Basin has been based on the historic sequence from 1892 to date.

In terms of water resource planning, the focus is inevitably on extended dry sequences or extreme dry individual years, as it is only in these circumstances that water becomes quite scarce. The significant storages in the southern Murray-Darling Basin, including the Snowy Mountains Scheme, provide reasonable capacity to cope with dry inflows in all but the most extreme conditions.

In any given year, water resource allocation is based on water in storage, water already consumed, and assumed worst-case minimum inflows for the balance of the year, allowing for worst-case losses for the remainder of the year.

Up to 2006, the "worst-case" inflow scenario was based on a sequence comprising the worst inflow in each month. Typically, monthly minimums had occurred in different years and this worst-case scenario was considered to be conservative.

In 2006, the historic basis for planning proved to be far too optimistic, as month after month historic minimum inflow records were not just broken but were literally smashed.

With the benefit of hindsight, the drought, which ended with a major flood in 2010/2011, dates to 1997. At the time, 2002–2003 was considered to be a bad drought year (the fifth driest on record at the time). However, the year had commenced with 4,000 GL in active storage and allocations of water for consumptive uses in Victoria, South Australia. For New South Wales (NSW), "high security" water rights had been only slightly reduced, relative to levels in non-drought years. Only irrigators in NSW with relatively low priority "general security" water allocations felt the pain, with only 10 % of the water supply they would have received in a year with full dams.

The next 3 years (2003–2004 to 2005–2006) saw below-average inflows, but allocations remained reasonable with total consumption limited to about 80 % of the long-term average.

Winter/spring of 2005 saw above-average rain. However, inflows were below average as a result of five consecutive years of dryness. By summer (December 2005), the weather had become hotter and drier than average. New Years Day 2006 saw 40 °C temperatures (104 °F), 100 km/hour winds, and evaporative losses from the river were at record levels. Summer and autumn were close to the driest on record but inflows were still within historic precedent.

By the start of the 2006–2007 water year (June 2006), inflows were at new record lows. Typically the southern Murray-Darling Basin receives the majority of its inflows in winter/spring and is very accustomed to hot, dry summers. By mid-spring 2006, the extent and impact of the extreme record low inflow was evident.

Inflows through winter and early spring had been only about 10 % of the long-term average and were significantly less than the minimum that had been used for planning up to that time. The Snowy Mountains Scheme had also received new record-low inflows and was reviewing the impact on future minimum estimates of its required annual release.

It was very clear that the southern Murray-Darling Basin and particularly the River Murray system was facing a level of water scarcity not experienced since the major storages had been constructed.

On 7 November 2006, the prime minister hosted a meeting of first ministers of the four basin states and the Australian Capital Territory.

The water ministers from the states and territory that are parties to the Murray Darling Basin Agreement, which governs basin water allocation and management, received a detailed briefing on the severity of the situation, including a forecast of what could happen for the balance of the current and next water years if the extreme dry conditions persisted.

24.3 Dry Inflow Contingency Planning

At the request of first ministers, the Senior Officials' Group for Dry Inflow Contingency Planning (SOG) was convened by the Australian government and comprised senior officials from each of the partner governments to the Murray-Darling Basin Agreement as well as senior officers of the Murray-Darling Basin Commission.

Early work by the Senior Officials' Group focussed on:

- identifying a new worst-case scenario to be used as the basis for future planning;
- identifying which towns and cities relied on surface water and to what extent, particularly if only "Critical Human Water Needs" (CHWN) and water for high-priority municipal industrial and stock demands could be met;
- reviewing estimated system losses under continuing extreme low inflows;
- identifying a broad range of contingency measures that could be implemented to ensure CHWN could be delivered;
- developing a better understanding of how risk management methodology could be used to support decisions that would need to be made;
- preparing comprehensive reports to communicate the complexity of the issues being addressed to Murray-Darling Basin state governments and other stakeholders.

It became apparent that the "normal" water-sharing rules set out in the Murray-Darling Basin Agreement would not necessarily deliver water equitably to all those relying on the River Murray System at a quality that would be suitable for drinking. The goal was to develop a strategy to deliver the CHWN for South Australia, estimated to be 201 GL, and 75 GL each for NSW and Victorian Murray valley towns.

A particular concern in dry inflow contingency planning was consideration of how water supply for the city of Adelaide in South Australia might be threatened under very low inflow scenarios and what contingencies to avoid this could be put in place. Adelaide has a population in excess of 1 million people and typically relies on the River Murray for about 40 % of its urban water. However, in times of drought, when inflows to its local storages are low, it can rely on the Murray for up to 90 % of its urban water. The major pumping stations supplying Adelaide are in the lowest reach of the River Murray, between Lake Alexandrina and Lock 1 at Blanchetown. These pumping stations are about 2,000 km downstream of Hume Dam, which is the major operating storage of the River Murray. Supplying water for Adelaide from Hume in extreme drought is challenging, because storage and evaporation losses from Hume Dam to the South Australian border are estimated to be at least 900 GL with an additional 350 GL of losses occurring between the border and Lake Alexandrina (just downstream of the Adelaide water offtake).

Net evaporation from the end of the system's lower lakes (Alexandrina and Albert) is typically about 800 GL in a dry year when local rainfall and inflows are low, and failure to replace this loss with flow leads to ecological damage in and around the lakes.

A further challenge for South Australia was water quality, particularly salinity. In the lower half of the Murray Valley, groundwater is typically saline and in many places it is as salty as the sea. Relatively small saline groundwater flows to the river can increase river salinities to above the 800 decisiemen (EC) target adopted in the late 1980s by the Murray-Darling Basin Commission as the goal for its salinity and drainage strategy. For extreme dry inflow contingency planning, it was agreed to aim for a target of no more than 1,400 EC at Murray Bridge, which is the site of the Adelaide water supply's most downstream pumping station.

Over the past 30 years, the Murray-Darling Basin Commission has funded the construction, operations and maintenance of a number of salt interception schemes that pump saline discharge from groundwater away from the river to evaporation basins. Together, these schemes prevent about 500,000 tonnes of salt from entering the Murray each year. Notwithstanding, the continuing operation of these schemes and the "salt holiday" as salt ingress from floodplains diminished due to falling water tables beneath floodplains as a consequence of prolonged drought, it was estimated that a minimum of 350 GL would need to flow to the lower lakes to achieve the salinity target. A simplified "worst-case" water balance for 2007–2008 water year in the River Murray is provided in Table 24.1. It is possible to address the shortfall through either improvements in inflows beyond the "minimum used for planning" or from contingency measures.

It was very apparent that managing evaporation losses would be more likely to boost water availability than managing water demand. Imposing restrictions on

Table 24.1 Simplified *Worst-Case* water balance for 2007–2008 in river Murray (GL)

Upper Murray inflows	485
Snowy inflows	373
NSW and victorian tributaries	188
Total inflow	1,046
Estimated end-of-season reserve	700
Total water available	1,746
Storage/river losses upstream of South Australian border	900
River loss South Australian border to lower lakes	350
Dilution flow to lower lakes	346
Critical human water needs	351
Total water required	1,947
Shortfall in water required	*201*

urban use for the city of Adelaide was estimated to reduce consumption by only about 10 GL per level of restriction in a five-tiered restriction system.

Dry inflow contingency planning was on the basis that only CHWN would be met, and in the “worst case” there would be no water for irrigation. The economic impacts of such a circumstance would be major, not just for the Murray Valley but for all three states that share the water of the River Murray.

The three subsequent years were dry—inflows were one-third to half of the long-term average but well in excess of the one-tenth of long-term average, which has been adopted as the “minimum used for planning” under the revised contingency plans. As a result, allocations for irrigation were about one-third of the long-term average in both 2007–2008 and 2008–2009.

24.4 Special Water-Sharing Arrangements

Through early 2007 as new record-low inflows were set each month, it was recognized by the Senior Officials Group that if the record low sequence was to persist through the winter/spring of 2007 then the existing rules would not equitably share the little water that would be available.

Until recently, the main legislation governing Murray-Darling Basin water was the Murray-Darling Basin Agreement. It did not include formal arrangements dictating exactly how water would be shared under extreme drought. However, it did include limited discretionary powers to enable revised water sharing and accounting arrangements to be implemented so that temporary arrangements could be developed. The new arrangements sought to ensure that water was initially available for all critical human needs, including stock and domestic water. Subsequent improvements in water availability would be used to:

- eliminate contingency measures,
- meet critical environmental needs, and
- make water available to irrigators.

The proposed special water-sharing arrangements were negotiated by senior officials from each state and submitted to water resource ministers in each state for approval.

Extensive communication of the process was implemented with summary reports to first ministers made publicly available. In addition, the Murray-Darling Basin Commission and the subsequent Murray-Darling Basin Authority issued comprehensive drought updates, which received wide media coverage. Each state also prepared and issued special briefing material for release to key stakeholders, highlighting issues of particular relevance in each state.

By November 2007, it was clear that the special arrangements agreed for 2007–2008 had served their purpose, and as inflows for the year were by then in excess of the minimum used for planning, attention could move to the 2008–2009 year.

The months of January to April 2009 were again extremely dry and set new record lows for these months. With opening season storages forecast to be only slightly higher than in June 2007, it was prudent to agree to an interim arrangement, pending development of the new water-sharing schedule that would extend special water-sharing arrangements for 2009–2010.

The negotiations of these arrangements were, if anything, a little more difficult than the previous 2 years. In the end, the agreed arrangements contained elements of both the previous two arrangements but tended to be more aligned with the original arrangements adopted for 2007–2008.

During the previous 2 years, Victoria and South Australia had introduced, as an interim measure, provisions for private carry-over of water not used in one year for use in the next year. NSW had for some years allowed carry-over for its general security users, but extended carry-over provisions to high-security users. The 2009–2010 special arrangements included provisions to ensure that carry-over in each state would be available equitably in all three states and thus avoid irrigators transferring water late in the year to another state to seek to improve reliability of access in the following year. The special arrangements were needed through June and July 2009 but by the time major irrigation diversions commenced in August 2009, there had been sufficient inflow, in excess of the minimum used for planning, for normal rules to be implemented.

24.5 Future Water-Sharing Arrangements

The Water Act (2007) represented a major reform to Murray-Darling Basin policy, providing additional commonwealth powers. The 2008 amendments to the Water Act included more formal provisions to ensure that critical human water needs could be met in future extreme scarcity scenarios. Such an approach recognizes that dealing with water scarcity conditions such as those experienced between 2007 and 2010 in the shared Murray system may well become more of a "business-as-usual" scenario in the future.

The new Water Sharing Schedule to the Murray-Darling Basin Agreement is more complex than interim arrangements agreed in each of the drought years (2007–2010) for one year only. It must cover all scenarios that are possible in the future, including scenarios involving drying due to climate change. A complication is that Murray storages can hold about one year's long-term average inflow and a little more than two years' long-term average use. A key feature of future dry inflow contingency planning is likely to be establishment of a "conveyance reserve" sufficient to ensure CHWN can be delivered for at least one year with inflows at the minimum used for planning and with otherwise exhausted reserves.[1]

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[1] The new Schedule for Water Sharing agreed in 2011 provides for a less conservative "conveyance reserve" of 225 GL.

The basin plan will include a determination of the volumes of Critical Human Water Needs for the River Murray System. The new Water Sharing Schedule to the Agreement will set out the rules for managing within three tiers of water management, which broadly encompass:

Tier 1: normal rules—water not scarce,
Tier 2: special rules to deliver CHWN—water scarce but not extreme or unprecedented, and
Tier 3: one-off emergency response to be agreed by Ministerial Council—water extremely scarce and unprecedented.

24.6 Lessons Learned

For more than a century, drought has been the prime driver for water reform in Australia. This recent record-breaking drought is no exception. Water management in the Murray-Darling Basin has changed and will continue to change for quite a number of years as lessons learned are incorporated into contemporary policy and practice. The lessons learned are substantial, although, with hindsight, quite a number may seem to be self-evident. They include:

24.6.1 The River Murray System is Less Reliable than we had Previously Thought

The inflows in 2006–2007 were so much less than those previously used for planning purposes that the initial response needed to be aimed specifically at trying to secure Critical Human Water Needs.

Longer-term response will need to consider revised management arrangements with a lower design yield and a more conservative reserve policy.

24.6.2 The Snowy Mountains Scheme Transfers are Important in Ensuring Critical Water in Drought

The Snowy Mountains Scheme is a major hydro-electric scheme to divert Australian Alp runoff into the Murray and Murrumbidgee that would normally not flow to these Rivers. It has a vital role in providing system reserves. The value of the Snowy Mountains Scheme in underpinning the Murray (and Murrumbidgee—the second largest Murray tributary) operations in times of water scarcity has been highlighted in this drought.

However, the recent drought also highlighted that in years when Snowy is unable to provide its required annual release, the River Murray would have to provide a reserve for conveyance losses. The only alternative would be to rely on future inflows that are not assured; thus, this is a risky approach to ensuring urban water supplies.

24.6.3 Low Inflows can Threaten Urban Security

Up until 2006, there was a high level of confidence in urban water supplies reliant on the River Murray. In the 2006–2007 water year total inflows, including Snowy transfers, were less than the system losses, including the entitlement for dilution and loss flow to South Australia.

Put simply, there was not enough inflow to operate the river for a full year, let alone provide for the CHWN of communities. It was only the opening reserves that allowed urban and restricted irrigation to occur.

24.6.4 Contingency Measures Should be Used Carefully to Minimize Ecological Impacts

A range of contingency measures were identified to ensure municipal industrial water supply and those adopted included:

- disconnecting wetlands to reduce evaporative losses;
- early pumping to Adelaide storages; and
- reducing flows below the normal minimum levels.

These contingency measures were implemented to assist with:

- reducing system losses;
- increasing volumes of water in upstream storage to improve likelihood of future recovery; and
- mitigating risks of potential deteriorating water quality as a result of low flow in the Lower Murray.

There were a number of other contingency measures that were seriously considered, but not adopted, including:

- disconnecting Lake Victoria;
- disconnecting the Edward River;
- procuring early release of Snowy water; and
- lowering weir pools.

A common feature of many items within this latter group of measures as well as the disconnecting of wetlands that did take place was that while water availability would be enhanced in the current year, the volume gained would need to be repaid in the future, and potentially at a time when water could be even scarcer. For example, disconnecting wetlands can significantly reduce losses initially, although, in the long term, the savings achieved need to be offset by the volumes required to refill the wetlands. In some wetlands, the beds of the wetlands proved to contain sulphidic sediments, which become sulphuric on drying. The long-term effects of such acidification can be substantial and are not easily reversed. In response to the emerging acidification risk, the former Commission undertook a comprehensive review of wetlands throughout the Murray-Darling Basin to identify those potentially at risk of acidification.

Consequently, while such measures have not been ruled out, they are considered "measures of last resort" and would only be used in an extreme circumstance in which CHWN could not otherwise be met. Such circumstance would be so dry that there would be no irrigation at all.

24.6.5 Water Trade and Carry-Over Reduce Economic Impacts of Drought

There is no doubt that water trade of allocation entitlements works to reduce the impacts of water scarcity on the economy (Connor and Kaczan 2013). It has been estimated that up to one-third of all water used in the southern Murray-Darling Basin in the past few years has been traded. The market certainly allows water to be traded towards its highest value use. The Productivity Commission has undertaken analysis and concluded that the impact of the drought on the economy has been halved through the wide use of water trade (Productivity Commission 2010).

Carry-over also played an important role in reducing the economic impact of drought. Prior to 2006 the only water entitlements that allowed an individual irrigator to carry-over water from one year to the next was NSW General Security Entitlement. Water not used by other irrigators was effectively carried-over by a state and reallocated across all irrigators in the following year. As a response to water scarcity since 2006, all water entitlements have been allowed to carry-over water to the following year. Further changes to policy relating to carry-over are being developed. The value of carry-over is evidenced by the substantial volumes of water carried-over (more than 400 GL in the Murray at the end of May 2009), even when total water use was only about 1,600 GL (compared with long term average of 4,200 GL in the Murray).

24.7 Conclusion: Planning for a Future Unprecedented in Hydrologic History

With inflows often at levels less than 60 % of previous minimums, the historic record may no longer be a reliable basis for making predictions about the likelihood of what may occur in the future. Many methods of analyses have been performed, but only time will tell which methods, if any, are appropriate. As part of the Australian government's Sustainable Yields Project, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Bureau of Meteorology (BOM) have developed methodologies to determine future "dry," "medium," and "wet" inflow sequences under possible future climate change scenarios. Interestingly, the historic inflow sequence in the southern Murray-Darling Basin from 1996 to date is similar to the driest sequences in the "2030 dry inflow sequence," developed by CSIRO/BOM (CSIRO 2008).

The Authority is now well advanced on developing updated sustainable diversion limits that will set new constraints of extractions for consumptive uses for all basin valleys. The experience with the recent drought suggests that if the future involves substantially less water than was available historically, additional work will be needed to modify the complex River Murray System critical human needs reserve water sharing rules. A number of processes are underway to review all the operational rules for the Murray and including a major review of the Murray-Darling Basin Agreement. Effective reform of the River Murray System requires the support of all four governments and takes time. Cooperation at all levels among governments has been an essential element of successful water management.

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Chapter 25
Potential Political Impacts in Southern California of Drought-Related Water Availability and Rate Increases

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Abstract A significant drought from 2007 to 2009, along with a federally-ordered restriction on water deliveries to California's largest agricultural and urban centers, has placed a substantial burden on many of California's water agencies. In response, the country's largest water agency in terms of the provision of drinking water—the Metropolitan Water District of Southern California (MWD)—along with its 26 member agencies enacted supply reductions that put significant upward pressure on water prices. One outcome of these supply reductions and rate increases is the increased need to further explore opportunities to generate supply through other channels, including recycling, water use efficiency, and desalination. Another outcome is that retail water providers are experiencing significant political pressure, and the number of people attending the public hearings continues to grow as the rate increases accumulate. This chapter presents a comparison of shortage allocation methodologies by member agencies and the related rate increase actions to provide insight into the challenges agencies will face until imported water supply reliability is improved.

25.1 Introduction

Water is critical to the day-to-day operations of existing businesses and to the viability of commercial enterprises and residential developments. From foods and beverages to toothpastes and medicine, water is the primary ingredient in hundreds of thousands of everyday products. Businesses must take into consideration the

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availability and quality of water when determining where to locate their offices or manufacturing facilities. The availability of water resources and service, therefore, has a profound effect on job creation. A scarcity of water resources can diminish or close existing businesses and hold up multi-million dollar developments, placing a severe strain on local economies. It is a fact that a safe, reliable water supply is central to the economic success of our communities, as will be highlighted below where the sustainability of agricultural operations in Southern California is challenged as are the development policies of particular cities.

It is no coincidence that water has been the centerpiece of controversial policies and political debates worldwide. From decisions to increase water rates at the municipal level, to discussing water politics on the international front, water has become a commodity whose scarcity can have crippling effects on the economy. Consequently, local governments are more readily working with national decision-makers to scurry for a solution that searches for new effective policies. This chapter presents an overview of some of the responses by Southern California water agencies to the drought-related water supply reductions. Additionally, the chapter reviews the general concepts of price demand management versus non-price demand management and how these methodologies result in political impacts affecting legislative proposals, public perception, and media coverage.

25.2 California Drought

From 2007 to 2009, California experienced a drought that ranked as the 12th driest three-year period in the state's history as measured by hydrologic record. This period also was characterized by unprecedented restrictions on water supplies at the state and federal levels. State water project (SWP) and Federal Central Valley Project (CVP) diversions from the Sacramento-San Joaquin River Delta (Delta), the main source of water for both the agriculturally thirsty San Joaquin Valley and Southern California, were restricted so as to protect listed fish species. These restrictions (and regulations) significantly exacerbated the impacts of the current hydrologic drought on urban, industrial, and agricultural water users.

The impacts of a single dry year such as 2007 on water supplies are normally minimal from a statewide perspective. Yet a dry 2008 combined with restrictions in SWP and CVP diversions from the Delta in response to a court-mandated implementation of an interim remedy to protect Delta smelt, led to the issuance of Drought proclamations and executive orders in 2008 and 2009 directing state agencies to take immediate actions to manage the crisis. The Department of Water Resources (DWR) was required to provide a report on the state's drought conditions and water availability. DWR subsequently committed to developing a drought contingency plan (DCP) to address the possibility of continuing dry conditions in 2010 and beyond. DWR has worked with other agencies and the legislature to develop the 20 by 2020 Water Conservation Plan which is a comprehensive plan to permanently reduce urban per capita water use 20 % by 2020.

The plan concludes that California can implement a range of activities designed to promote legislative initiatives that provide incentives to water agencies to implement water conservation and water use efficiency through technological or behavioral improvements in indoor and outdoor residential, commercial, industrial, and institutional water use. Such activities are meant to lower demand and per capita water use, which will have a positive effect on available water supplies and their quality (CDWR 2010).

In addition, a new U.S. Fish and Wildlife Service biological opinion for Delta smelt released in December 2008 called for measures that would result in an estimated 20 to 30 % reduction in SWP and CVP Delta diversions on average. Observed precipitation in January 2009 was about one-third of the average, indicating that the threat of a third year of drought was becoming a real possibility. These conditions, coupled with statewide reservoir storage levels approximately 35 % below average, led to the governor's proclamation of a statewide water shortage state of emergency in February 2009 (CDWR 2009).

25.3 Water Supply

The Metropolitan Water District of Southern California (MWD) is the nation's largest provider of treated drinking water. Each day during a normal year, MWD moves more than 1.5 billion gallons of water through its distribution system, delivering supplies to 26 member agencies. Member agencies, in turn, sell water to more than 300 sub-agencies or directly to consumers. In all, 19 million Southern Californians rely on MWD for some or all of the water they use in their homes and businesses (MWD 2010).

Since July 2007, MWD has been working cooperatively with its 26 member agencies to develop a formula and implementation plan to allocate water supplies to the member agencies in the event of a water shortage. MWD focused its member agencies on deciding how to apportion the resulting water supply shortage in 2009. Ultimately, MWD enacted a 20 % supply reduction in 2009 relative to a 2004–2006 baseline period.

The reduction in water sales revenue put significant pressure on MWD to raise rates during the same period. MWD board voted to increase prices for its 26 member agencies by 19.7 % beginning September 1, 2009. Another rate increase of about 20 % is expected sometime in 2011, both to cover revenue shortfalls and costs such as pumping, treatment and the canals that carry water from the Delta, even if water is not delivered. The decision follows a 14.3 % rate increase in early 2009 (Zimmerman 2009). In response to these rate increases by MWD, most MWD member agencies passed the rate increase onto their customers based on their continuance of expensive imported water delivered to their customers in amounts that reflected their mix of less-expensive local groundwater to MWD imported water.

Further rate increase pressure is being placed on retail water agencies as they look to construct more costly local projects to offset the loss of the imported MWD water. Local projects include recycling, increasing water use efficiency, groundwater harvesting, desalination, and stormwater capture. Meanwhile, retail water providers are experiencing significant political pressure as a result of these extreme rate increases. State law (Proposition 218) requires a specific public notification and public comment period when agencies implement rate increases. The number of commenters' attending the public hearings continues to grow with each additional rate increase water agencies pass on to their customers. As potential Bay-Delta improvements to restore imported water supply reliability are at least a decade away, local water providers will be under increasing political pressure as they deal with annual rate increases and the implementation of policies related to water supply restrictions. As a consequence, agencies will experience more interest from potential candidates to their elected boards and councils.

More importantly, as water supplies are reduced and water prices rise, Southern California's water supply problem will continue to affect the economies that depend on it. Businesses that depend on water as a primary input into the production process (e.g., the agricultural sector) are the hardest hit. Some water agencies have considered shutting down local economic development altogether. Areas of the state experiencing the greatest irrigation water shortages or drought-related impacts in 2009 were located on the west side of the San Joaquin Valley and in the San Diego/Riverside County avocado and citrus growing area (CDWR 2009).

MWD has a long history of providing discounted rates for its agricultural users under the Interim Agricultural Water Program (IAWP) which offers a discounted rate for surplus system supplies available for the purpose of growing agricultural, horticultural, or floricultural products. Agricultural deliveries represent approximately 5 % of MWD's 2007 deliveries and contributed approximately $200 million in revenue over the years 2003-2008. The primary justification for lower rates has been interruptibility, as water for agricultural uses was and is considered to be a surplus sale, subject to interruption in service. This program was put into place in 1994. Yet given the region is in shortage currently, there is no longer a surplus in supply; hence, for the first time under the Interim Agricultural Water Program, MWD called on the agricultural sector to reduce their water use by 30 %, effective January 1, 2008, and implemented a five-year complete phase-out plan from 2008–2013. As of January 2013, this program will no longer exist (MWD 2008).

Another area of concern in Southern California is the growing community of Temecula. Since 2000, Temecula has had a population growth of 75.1 % and at a population of 101,057 (City of Temecula), water is a key component of this expanding local economy. Facing a water shortage related to economic growth, the Rancho California Water District in Temecula considered a moratorium on any new meters and service guarantees for new development of prospective residential and commercial business customers. Ultimately, after much debate and public outcry, the Board of Directors rejected the moratorium. The 5-2 vote by the Rancho California Water District board was vigorously debated during a 3 hour public hearing in which dozens of developers, public officials, and other stakeholders spoke for and against the proposed action. Proponents of the moratorium argued that the district would not be a responsible agency by asking its current customers to conserve water when the district agrees to take on new demand. But critics said the moratorium would do little to solve the region's water woes by stunting regional jobs and economic growth. The majority of board members of the Rancho California Water District believed it could not support a moratorium and that other methods of water conservation and supply management methods should be studied (Horseman 2009). While action was not taken to restrict meter sales, the issue reminds us that a significant policy question looms in front of us: what changes in the methods of supplying water to new development must be considered if and when persistent water shortages become a reality?

25.4 Supply Management Projects

Examples of supply management projects include desalination and recycled water. These types of projects have extremely high capital outlay but provide a significant long-term solution to the current water supply problem facing the state of California.

25.4.1 Desalination

Desalination in Southern California has evolved into a desirable water supply alternative by tapping one of the largest reservoirs in the world—the Pacific Ocean. Though the technology has been available for decades, significant advances have greatly reduced operating costs related to the large amount of energy required for desalination. This technology is at work in many arid areas of the world, including Australia, the Middle East, the Mediterranean, and the Caribbean (Poseidon Resources 2004–2011).

This technology can be found in Southern California at the Carlsbad Desalination Project. This project consists of a planned 50 million gallon per day (56,000 acre-feet per year) seawater desalination plant and associated water delivery pipelines. The project is located at the Encina Power Station in the city of Carlsbad, a coastal community in Southern California. The privately financed project will produce enough drinking water for 300,000 San Diegans annually and provide San Diego County with approximately 10 % of its total water supply. In August 2008, the facility secured the necessary state permits to proceed with construction and is slated to be operational in 2013. The objectives of the desalination project include providing a local source of potable water to supplement imported water supplies, improving water supply reliability, improving water quality, and complementing local and regional water conservation and water recycling programs (Poseidon Resources 2004–2011).

In November 2009, MWD's Board of Directors voted to approve a Seawater Desalination Program agreement with the San Diego County Water Authority and nine local retail agencies. The agreement provides the nine local water retail agencies, known as the San Diego Desalination Partners, with a $250 per-acre-foot incentive towards the purchase of desalinated water from the Carlsbad Desalination Project based on project production for agreement terms up to 25 years; and schedule project production according to regional need (Poseidon Resources 2009).

25.4.2 Recycled Water

Use of recycled water from sewage treatment plants can defer large amounts of new water usage during critical times, thereby effectively supplementing the water supply. Recycled water benefits include the reduction of dependence on imported water, a new source of irrigated water, diversification of the water portfolio and, most importantly, a source of water that is locally reliable even in times of drought.

Agencies all over Southern California are investing hundreds of millions of dollars in recycled water technology. Leading the way is the state-of-the-art groundwater replenishment system (GWR System) in Orange County. The GWR System takes highly treated wastewater that was previously released into the ocean and purifies it through the use of microfiltration, reverse osmosis, and ultraviolet light with hydrogen peroxide advanced oxidation treatment. These processes produce water similar in quality to bottled water. The purified water will become part of a seawater barrier and will be pumped through a 13-mile pipeline to spreading basins in Anaheim, where it will percolate into deep aquifers and blend with Orange County's other sources of groundwater, following the same natural filtering path rainwater takes through the ground (OCWD 2002).

25.5 Water Demand Management

As opposed to supply management, in which the primary strategy is to meet demand by increasing supply, the primary objective of demand management is to control water use, reduce waste, and increase use efficiency and equity in view of limited supplies. The tools for water demand management are price and non-price conservation programs. In "Comparing Price and Non-Price Approaches to Urban Water Conservation," Yale University's Sheila M. Olmstead and Harvard University's Robert N. Stavins found that pricing reduces water use more cost-effectively than a command-and-control system.

> Urban water conservation is typically achieved through prescriptive regulations, including the rationing of water for particular uses and requirements for the installation of particular technologies. A significant shift has occurred in pollution control regulations toward market-based policies in recent decades. We offer an analysis of the relative merits of market-based and prescriptive approaches to water conservation, where prices have rarely been used to allocate scarce supplies. The analysis emphasize the emerging theoretical and empirical evidence that using prices to manage water demand is more cost-effective than implementing non-price conservation programs, similar to results for pollution control in earlier decades. Price-based approaches also have advantages in terms of monitoring and enforcement. In terms of predictability and equity, neither policy instrument has an inherent advantage over the other. As in any policy context, political considerations are important.

According to Olmstead and Stavins, a city can conserve water by raising prices, in which case it will have more water and more revenue if demand is inelastic. The city may adopt water conservation rules, in which case it will have more water but less money.

> Non-price management techniques can create political liabilities in the form of water-utility budget deficits. Non-price conservation programs are costly. In addition, if these policies actually reduce demand, water utility revenues decline. During prolonged droughts, these combined effects can result in the necessity for substantial price increases following "successful" non-price conservation programs, simply to prevent water utilities from unsustainable financial losses. This occurred in 1991 in Southern California. During a prolonged drought, Los Angeles water consumers responded to the Department of Water and Power's request for voluntary water use reductions. Total use and total revenues fell by more than 20 %. As a result, the Department requested a rate increase to cover its growing losses. In contrast, given urban price elasticities common in the United States, price increases will increase water suppliers' total revenues. The extra per-unit revenues from a price increase outweighs lost revenue from the reduction in quantity demanded (Omstead and Stavins 2008).

MWD did not raise water rates from 1996 through 2003, primarily due to higher than anticipated water sales, even though costs continued to rise. Beginning in 2004, due to continued rise in operating cost and dwindling surplus, MWD was constrained to impose higher water rates on an annual basis. These rates ranged from as modest as 1.6 % a year to as high as 19.7 % a year by 2009. As part of its 2004 Long-Range Finance Plan, MWD expected overall rate increases to average between 3 and 5 %. From 2004 through 2007, rate increases averaged 2.9 %. During that same period, inflation (as measured by the CPI for Los Angeles-Riverside-Orange County) increased by an average of 3.9 % per year. Hence, there was little to no increase in the real price of water. However, given the need to ensure that revenues match expenditures, MWD raised rates in January 2008 by 5.8 %, followed by a 14.3 % increase in January 2009. Two additional rate increases of 19.7 % each were implemented in September 2009 and January 2010.

Omstead and Stavins mention three categories of non-price conservation programs water utilities can implement: (1) required or voluntary adoption of water conserving technologies in which water utilities influence customer adoption of low-flow technologies such as faucet heads and low-flow toilets, (2) mandatory water use restrictions which enforces limited water use, usually outdoor restrictions on irrigation and car washing, and (3) mixed non-price conservation programs that are programs that consist of water restrictions, landscape education, and low-flow fixture distribution programs (Omstead and Stavins 2007).

An objective of a number of water demand management strategies implemented by agencies in Southern California has been on improving water use efficiency through conservation programs, as evidenced, for example, in the Water Conservation Act of 2009. Through public education, behavioral change, technology, and improved landscape design consumers can conserve water and reduce water usage, which will lead to a lower water demand (CDWR 2010). Western Municipal Water District has adopted a Water Use Efficiency Master Plan that offers incentives and programs that include: SoCal Water$mart Program for single-family residential water-efficient measures; the Save Water—Save A Buck Program for multi-family and commercial water efficient measures; the Water Savings Performance Program for industrial process and irrigation system improvements; the Public Sector Program offering public agencies four components (water audits, enhanced incentives, pay for performance incentives and recycled water hook up incentives); the California Friendly Homes Program offering developers incentives for water-efficient measures; the Turf Replacement Program for removal of high water use turf and replacement with low-water using plants and low-precipitation irrigation systems (WMWD 2008).

Affecting a sustainable decrease in customers' water consumption is not a single-action process. Each customer group has unique needs and motivations that, if tapped into correctly, can provide a positive outcome for all involved. If all agencies reduce overall water consumption, stretching the supply to accommodate new demands, all customers may benefit economically as the revenues required to run agency programs can be spread out over more customers; consequently, the pressure to increase prices is assuaged. A successful water-use efficiency master plan puts together an aggressive collection of customer-tailored demand management solutions designed to achieve long-term water efficiency and change customer daily water-use routines.

25.6 Legislative Action

California's Department of Water Resources announced in December 2009 an initial allocation of 5 % of total contracted water deliveries to the SWP contractors for 2010. This is the lowest percentage since the SWP began delivering water in 1967. A month before the announcement, the California legislature along with Governor Arnold Schwarzenegger attempted to mitigate the problem by passing the Safe, Clean, and Reliable Drinking Water Supply Act of 2010 to meet California's growing water challenges. A comprehensive deal was agreed to, representing major steps towards ensuring a reliable water supply for future generations, as well as restoring the Sacramento-San Joaquin Delta and other ecologically sensitive areas.

The measure is composed of four policy bills and an $11.14 billion general obligation bond. The package establishes a Delta Stewardship Council, sets ambitious water conservation policy, ensures better groundwater monitoring, and provides funds for the State Water Resources Control Board for increased enforcement of illegal water diversions. The bond will fund seven categories, including drought relief, water supply reliability, Delta sustainability, statewide water system operational improvement, conservation and watershed protection, groundwater protection and water quality, and water recycling and water conservation. While the water bond measure, officially labeled Proposition 18, was approved both the State Senate and State Assembly as a comprehensive water package and was to be put on the November 2010 ballot, legislative leaders have since signaled their intent to postpone the water bond until November 2012, citing the need to focus on the state's budget woes for fiscal year 2010–2011 (Lien-Mager 2010).

According to Jim Carlton of the *Wall Street Journal*, the water package was controversial in part because of a provision in the bond deal to use about $3 billion for new storage projects, which could include dams. Democrats, who dominate the statehouse, have largely opposed new dams, while Republicans led by Governor Schwarzenegger, have supported them. The deal to include money for possible dams was one of the compromises in the package. Another compromise came on the issue of mandatory monitoring of the state's groundwater supplies, which are often tapped during times of drought. Many Democrats wanted the monitoring, which has been optional, done by the state if local agencies failed to do it. But some Republicans insisted the monitoring be handled locally to help allay fears among some water agencies of too much state intrusion. Under the deal, local agencies will do the monitoring (Carlton 2009).

Potential solutions will change the political climate surrounding water and agencies will have to answer unpopular questions and make tough choices. Water shortages and drought are not only tough issues within themselves but the state faces obstacles that will play a major role in determining a solution. The state faces a growing population, requirements to protect endangered species, demands to clean up the Delta, and responsibility to allocate funds and ensure that agencies make the appropriate decisions for an area (PPIC 2009).

Instability in the Delta poses a serious threat to the economies of the San Francisco Bay Area, Southern California, and the San Joaquin Valley. Weak Delta levees and high saltwater content, along with water quality issues, signal the grave condition of the region. Since 2007, the collapse of native fish species has led to court-ordered cutbacks of pumping from the southern Delta. The Delta's physical deterioration will not be delayed by political indecision. California has the tools to help secure a safe and reliable water supply, improve conditions for aquatic species, and reduce flood risks. In recent years, water managers have made significant progress in addressing these goals. But the challenges are increasing with population growth, climate change, and environmental concerns. Stepping up the momentum in policy reform is essential for the state's future. According to the

Public Policy Institute of California, the state must look ahead to the following solutions:

Resolve the Delta crisis. A peripheral canal has the best potential for safeguarding the Delta's environment while maintaining water supply reliability. But this solution requires solid policies on governance, finance, and mitigation of Delta landowners and residents.

Increase water efficiency incentives. Current state efforts to reduce per capita water use by 20 % by 2020 can be furthered with better pricing policies.

Strengthen groundwater management. Better basin management is a prerequisite to realizing the significant potential of groundwater banking. State proposals to require the reporting and monitoring of groundwater use could foster better management.

Increase local incentives to lower flood risk exposure. To reduce risks to new development, state floodplain mapping should account for climate change and increasing flood risks. More forward-looking federal policies will also be important to account for changing flood risks.

Improve responses to a changing climate. Higher water temperatures and sea level rise will alter aquatic habitat in significant but largely unexplored ways. Environmental laws will require that water users respond to these changes with potentially costly management actions (PPIC 2009).

25.7 Public Perception

California's Legislative Analyst's Office stated that since 1996, voters have approved more than $14 billion in general obligation bonds for water-related purposes. Prior to 2006, water bond funds were allocated among the CALFED Bay-Delta Program (largely focused on the San Francisco Bay/Sacramento-San Joaquin Delta estuary) water quality and water management activities. However, recent bonds have not provided funding openly for CALFED. They have, in its place, funded water quality and environmental enhancements while placing an increased focus on water management. The concluding category addresses water supply, flood control, and water conservation/recycling requirements. The increased emphasis on water management also is reflected in bond funding through local assistance to the integrated regional water management program (IRWM). Under IRWM, local agents/agencies submit to the state a regional water management plan addressing issues including water supply reliability, water use efficiency, and storm water and flood control, among others in order to become eligible for bond funds for projects identified in the regional plan. The program is jointly managed by the Department of Water Resources and the State Water Resources Control Board (LAO 2008).

The Association of California Water Agencies stated in a March 2000 article, titled “California Water: The Looming Crisis,” that Californians are in definite support for water programs by voting for bonds that will fund water management and conservation. This article observed that for the second time in less than five years, Californians have shown support for dramatically improving the state’s water infrastructure. The article highlighted the fact that in March 2000, voters overwhelmingly approved Proposition 13, the $1.97 billion water bond. This measure was a critical step toward improving the water infrastructure to support California’s future growth. The purpose also was to restore one million acre-feet of water to cities and farms during a dry year. With other challenges in the current time, public perception has only gained more momentum in the need to persuade state and federal leaders to address these critical water issues (ACWA 2000).

25.8 Media Coverage

Media coverage on drought and rate increases has a direct impact on politics; it can affect candidates and current officeholders alike. Even more importantly, media coverage can influence voter decision making on important issues. An Internet search on “drought-related water availability”, showed a staggering 772,000 world-wide references. Closer examination reveals the top sources are from entities such as the Environmental News Service (California Faces Water Rationing, Governor Proclaims Drought Emergency 2009); Office of the Governor (California Faces Water Rationing, Governor Proclaims Drought Emergency June 2008); Water Webster (U.S. Drought News); Southern California Agricultural Water Team; ACWA News (California Drought January 2009); and Tree Hugger (Southern California Facing the Perfect Drought). A similar search for one of the wetter states in the United States, Alabama, revealed just 182,000 hits, an amount far less than in California where water issues garner more media coverage. Another popular topic in the U.S. news, water rate increases, garnered a whopping 1,310,000 references on the Internet. Most articles were of the straight-forward and factual basis providing information about upcoming rate increases at a specific water district.

Opinion pieces and letters to the editor also contribute in our news-saturated world, particularly online versions that are accessible at just the click of a mouse. Tim Quinn, director of the Association of California Water Agencies (ACWA), wrote a 2007 opinion piece titled, “Dry Times Ahead”, published by the *Inland Empire Community Newspaper*. As the piece was written and published prior to the current crisis, of note is the last paragraph shown here that discusses the need for a public education program.

> When the rest of the world thinks of Southern California, it thinks of beaches, of swimming pools, of …water. Water has always played a major role in life in the Southland. And with good reason—without a steady supply of imported water, Southern California wouldn’t exist as we know it today.

> Because the entire region depends heavily on this important resource, there is growing concern about the region's economy, quality of life and environment will fare in the face of a deepening, statewide water crisis. Experts are warning that California's water problems are so serious that many parts of the state, including the Southland, may soon be facing water rationing and reduced supplies.
>
> State leaders and environmental authorities agree that California's statewide water system is in crisis. Yet despite intense media coverage and focus by the governor and legislators, the public remains unaware of the state's water problems. That's why a statewide coalition of 450 public water agencies recently decided to launch a public education program to inform people about critical challenges now confronting the state's water supply and delivery system. These challenges affect each and every Californian, and we can no longer afford to ignore them.

The public education program was indeed launched by the California Water Awareness Campaign, an arm of ACWA, called Save Our Water (SOW). The SOW campaign instituted a variety of media for outreach including a website, paid advertising, social media sites, such as Facebook, public events, and earned media, and unpaid media coverage in the form of stories and articles.

The earned media results were impressive as marked by numerous significant accomplishments. The April 2009 launch was covered by a variety of print, TV, and radio outlets. Since the launch, the program has issued several news releases, including releases on the State Fair exhibit, "Save Our Water" day. Opinion pieces have been successfully pitched to the following media outlet: *Sacramento Bee*, *Folsom Telegraph*, the *Marysville Appeal-Democrat*, *California Counties* magazine, and the *Western Cities* magazine. Media impressions appeared in 40 newspaper articles, eight television news clips, and four radio news clips. The SOW Dusty Baker public service announcements aired on radio and television stations throughout the state in spring 2009.[1] Some local water agencies used the radio and television ads as part of their local programs, as well as Dusty Baker print ads. People listen and act accordingly and, given the magnitude of media coverage, the subsequent impact on action directly related to media coverage may be significant. People also base their opinion and their vote not just on their ideals, but on the influence of the "village voice."

Television commercials also have the potential to make an impact. MWD has used media to do an array of water use efficiency related commercials during its annual media blitz. With a half million dollar budget, MWD ran a 12-week campaign focused on water use efficiency. Although the context of the topic is not directly related, the outcomes of the campaign are worth noting as they provide a clear perspective on the impact of this media campaign. This media campaign ranked fifth when an online search for "conservation" was done. (To be listed in the Top 10 on a web search equals great success.)

Through the social media marketing arm of the campaign, MWD secured 1.4 million followers. Respondents to the MWD online questionnaire reported that they were 63 % more likely to reduce water use after viewing the ads. In talking

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[1] Dusty Baker is a well-known ex-Los Angeles Dodgers baseball player who grew up in Southern California.

with 800 participants, the MWD advertising produced the following results: eight out of 10 recalled seeing the ads; 82 % indicated they had heard about the drought, water shortages, and the need for conservation; after viewing the advertising, nine out of 10 took action; and seven out of 10 are using less water.

On the flip side, advertising and subsequent media coverage can have potentially adverse impacts on residents' perceptions and thus may spill over in their actions at the polls. "The Great Delta Toilet Bowl" advertising campaign, both print and television, which was done by the Families Protecting the Valley group in Northern California, has set off a large controversy. Regardless of facts or fairness of the campaign, which is designed to target wastewater agencies in the Delta that are allegedly dumping wastewater high in contaminants into the Delta region, advertising gets heard and read. Associations, such as the California Association of Sanitation Agencies (CASA), are preparing to take a position and possible action in response.

The difficulty lies in determining the best approach to effectively message to customers and the general public. Any agency that attempts to rebuff the slanted campaign surely opens itself up to questions and spotlighting. For instance, an agency seeking to do a counter campaign could seek the high road, promote responsible environmental stewardship and a highly regulated industry. A campaign would need to be educational and science-based. Avoiding the low road is critical, as it may lead to emotional or political responses. What does this all point to? The ability for advertising, campaigns and earned media to dramatically impact public perception, whether right or wrong, accurate or not. Perceptions can often become reality, particularly at the polls.

25.9 Conclusion

Water managers and water policy makers are faced with a number of challenges related to significant water supply reductions, pressure to change the rates they currently charge for water, in addition to customer and public perceptions which are influenced by an increasingly easy access to media outlets, particularly web-based. If solutions to reduced availability to imported water and increased available local water supplies are not forthcoming, significant impacts to the economy and lifestyle in Southern California will become a reality.

Elected officials and policy makers will feel increasing pressure from the public as water rates to retail customers, residential and businesses continue to rise at rates well above inflation. If large-scale water outages occur, that pressure could affect changes at the local election booth.

Rate increases can and have been used with some success, but long-term solutions to California's thirst for water must be addressed. Implementing best management practices, effective public communication programs, as well as strong and courageous policy leadership will also be necessary to overcome the challenges before us. Our inabilities to take the appropriate actions may severely impact our way of life in Southern California, which is dependent on water for household consumption, business production, and continued economic growth.

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Chapter 26
Drought and its Role in Shaping Water Policy in Australia

Matt Kendall

> I love a sunburnt country, A land of sweeping plains, Of ragged mountain ranges, Of drought and flooding rains. —My Country by Dorothea McKellar.

Abstract The classic poem about Australia was penned by Dorothea McKellar in the early years following Australia's birth as a nation and in the shadows of the infamous 1895–1902 Federation Drought. A century later, Australia again found itself in the grip of a drought that tested the resolve of Australia's Federation in several capital cities and across the iconic Murray-Darling Basin. In both the Federation and the recent 1996–2009 "Millennium" drought, severe water shortages have catalyzed reform of Australia's water sharing arrangements. The chapter explores the evolution of water management in Australia, including the intergovernmental governance arrangements in the Murray-Darling Basin, the 1994 Council of Australian Government water reforms, the 2004 National Water Initiative and the establishment of the Commonwealth Water Act. In conclusion, current progress and challenges for future water reform in Australia are discussed.

26.1 Introduction

26.1.1 Australia's Water Resources

Australia is the driest inhabited continent in the world; rainfall is extremely variable and droughts are common. The Australian community is all too aware of this situation as a result of the extended dry conditions experienced across much of the heavily populated and agricultural regions of the country during the past decade. With these pressures on the environment and economy, the Intergovernmental Agreement for a National Water Initiative (NWI) was signed in 2004 by the

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Table 26.1 Ratio of maximum annual flow to minimum annual flow for selected rivers

Country	River	Ratio between maximum and minimum annual flows
Brazil	Amazon	1.3
Switzerland	Rhine	1.9
China	Yangtze	2
Sudan	White Nile	2.4
USA	Potomac	3.9
South Africa	Orange	16.9
Australia	Murray	15.5
Australia	Hunter	54.3

Source Chartres and Williams (2006)

Australian government and all state and territory governments as the blueprint to better manage Australia's scarce and valuable water resources. The National Water Commission (the Commission) has a key role in implementing the requirements of the National Water Commission Act of 2004, and the Intergovernmental Agreement for a National Water Initiative (NWI).

Development across Australia depends on access to water resources that are far more variable in volume and quality than in other parts of the world. Previous studies of global water availability have shown that the total runoff from Australia is an order of magnitude more variable than from most other continents, while the actual runoff is less than a quarter of that from any other continent (NWC 2007a), (Table 26.1).

Water availability in Australia is characterized by its scarcity, and temporal and spatial variability. Runoff in Australia averages 45 mm: only about 1/4 that of Africa, 1/7 that of Asia, Europe and North America, and only 1/14 that of South America. Australian streams exhibit annual variability of about double those of the rest of the world. The coefficient of variation of annual flow volumes, defined as the standard deviation divided by the mean, averages 0.7 in Australia, compared to the world average of 0.43. This variation translates into erratic flows composed of periods of drought often followed by floods rather than steady flows throughout the year.

Spatial distribution of runoff across Australia is also highly uneven, being concentrated along the northern coasts of Western Australia, Northern Territory and Queensland, and the west coast of Tasmania. Runoff from the southern and eastern remainder of the country, including the major population centers of Sydney, Melbourne, Perth, Adelaide and Canberra, as well as the Murray-Darling Basin, which contains approximately 70 % of Australia's irrigated crops and pastures, is less than a quarter of the country's total (NWC 2007b).

Recurrent droughts and consequent long periods of low flows have made it essential for governments and water authorities to build large dams to maintain supply to communities and agriculture. Rivers in southern Australia are extensively dammed and regulated to provide year-round security of supply for urban and domestic use, and irrigation water for use during the summer (Harris 2006). As a result of this high variability, Australia stores up to seven years' worth of water supply in its major dams in order to ensure consistently reliable water supply (NWC 2007b).

26.1.2 Water Use in Australia

Compared with many other developed countries, a significant portion of Australia's water is allocated to agriculture, mostly irrigated crops (Fig. 26.1). The amount of water used in Australia per capita for domestic and residential purposes is lower than in, the United States, New Zealand and Canada, but higher than in most European countries (UN Food and Agricultural Organization 2005).

In 2004–2005, total water use in Australia was 79,784 GL. Of that volume, 62,445 GL was defined as in-stream use (water was used and then returned to the environment after uses such as hydroelectric power generation), and 18,767 GL was defined as consumptive water use. Consumptive use was allocated across sectors as follows (NWC 2007a):

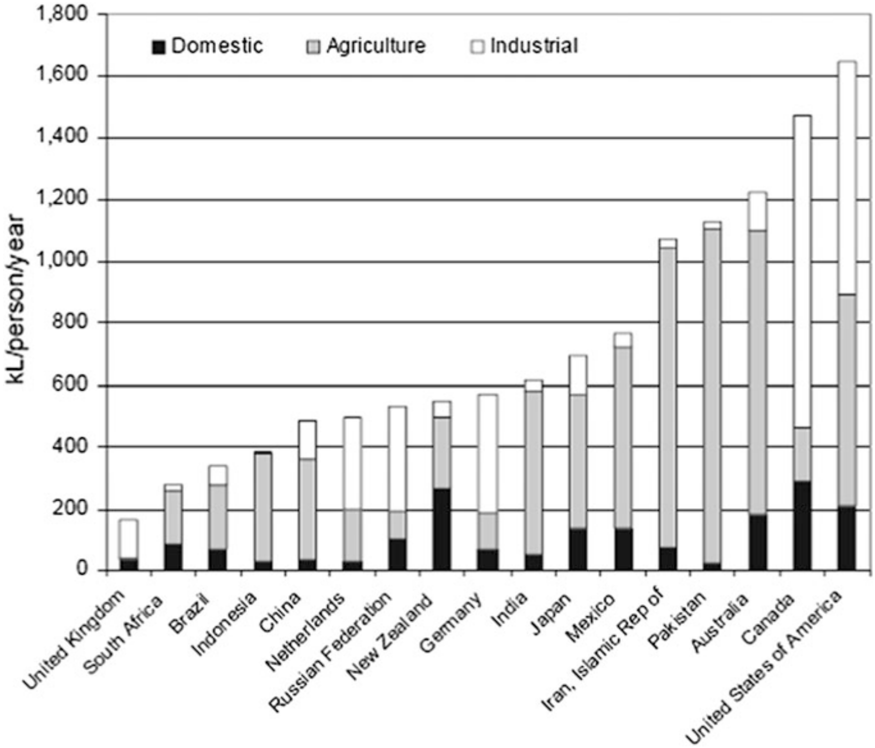

Fig. 26.1 Water use per capita by sectors for selected countries. *Source* UN Food and Agriculture Organization 2005

- Agriculture—65 % (12,191 GL)
- Households—11 % (2,108 GL)
- Water supply industry—11 % (2,083 GL)
- Other industries—6 % (1059 GL)
- Manufacturing—3 % (589 GL)
- Mining—2 % (413 GL), and
- Electricity and gas—1 % (271 GL).

26.1.3 The Role of Drought in Shaping Water Policy in Australia

Drought has played a major role in shaping water policy in Australia, from the influence of the 1895–1902 Federation Drought on the drafting of Australia's Constitution through to the influence of the 1996–2009 Millennium drought on the major reforms, including the 2004 National Water Initiative and the 2007 Commonwealth Water Act. While Australia has experienced numerous droughts since European settlement, these two droughts are among the longest, most severe, and also most significant in terms of the influence on Australia's federal system of water management. The Federation Drought will be considered briefly; the recent Millennium Drought will be discussed in more detail so as to assess the effect of drought on Australian water policy—past, present and future.

26.1.4 Australia's Federation Drought 1895–1902

Many of Australia's worst droughts occur when one or two very dry years follow several years of generally below-average rainfall. Such was the case in the so-called "Federation Drought," which began in the mid 1890s and reached its devastating climax in late 1901 and 1902 (BoM 2009).

The 1902 drought was considered Australia's greatest natural disaster to that date, and the famous Australian singer Dame Nellie Melba, returning from several years travel in Europe was reportedly shocked and disgusted by the suffering she witnessed as she toured outback areas by train. Her observations included, "I had noticed out of my window the carcasses of sheep and cattle lying dead and rotting under the gum trees whither they had crawled to eat the leaves. And when they could reach no more they dropped dead" (McKernan 2005).

The climatic characteristics and major impacts of the Federation Drought are described by Australia's, BoM (2009):

> The five years leading up to Federation (January 1901) saw intermittent dry spells over most of the country, particularly in 1897 and 1899; in most of Queensland, dry conditions were virtually unbroken from 1897. Most other parts of the country had reasonable rain in 1900 and early 1901, but with the coming of spring 1901 very dry weather set in across

> eastern Australia. By February 1902 concerns were expressed about Sydney's water supply, and the New South Wales Government declared 26 February a day of "humiliation and prayer" for rain in that state. Similar declarations were made in Queensland in April and Victoria in September, as the drought worsened.
>
> Despite the pleas for divine intervention, things only got worse. Though there was some winter-spring rain in Victoria and NSW, cold weather nullified its usefulness. In Queensland, enormous sheep and cattle losses were being reported by August. On some far western properties, cattle numbers plummeted from tens of thousands to mere hundreds. Rivers in western Queensland dried up; at Bourke, the Darling River virtually ran dry. Further south, towns near the River Murray such as Mildura, Balranald and Deniliquin—at that time dependent on the river for transport—suffered badly. The Australian wheat crop was all but lost, with close to the lowest yields of the century.
>
> The drought began to break in mid-December when heavy general rain fell in Victoria, with more after Christmas. Rains extended to NSW and southern Queensland, while northern Queensland had reasonable falls from December onwards.
>
> In Queensland, the 1902 drought was the culmination of eight years that were dry more often than not over most areas. These years had a devastating effect on stock numbers: sheep numbers fell from 91 to 54 million, and cattle from 11.8 to 7 million. The drought began focusing minds on irrigation, especially in the three states through which the River Murray flows: but it wasn't until the next severe drought in 1914 that the River Murray Commission was created.

The Federation Drought provided the backdrop for discussion of potential water management arrangements at the 1897/1898 Australian Federal Convention, where the focus was on three interrelated issues focusing on the River Murray—water for irrigation, stock and people, the protection and enhancement of riverboat navigation activities and the relationship of both issues to the competing rail networks of the two eastern states (Connell 2007).

At the Federal Convention, significant time and effort was spent debating responsibility for water management with a focus on the water-sharing arrangements of the River Murray. The upper states of New South Wales and Victoria did not want any restriction on their rights to utilize the Murray, while South Australia as the downstream state wanted provisions to ensure adequate water for irrigation and riverboat navigation. The final outcome of the lengthy debate was Clause 100 of the Australian Constitution:

> Clause 100—The Commonwealth shall not, by any law or regulation of trade or commerce, abridge the right of a State or of the residents therein to the reasonable use of the waters of rivers for conservation or irrigation.

Of note, the inclusion of the term "reasonable" has provided the basis for more than 100 years of ongoing negotiation and debate to interpret and strike an appropriate balance in the water-sharing arrangements for consumptive use between the lower and upper states, and more recently between consumptive users as a whole and the environmental needs of the rivers and wetlands of the Murray-Darling Basin.

26.1.5 Evolution of Murray-Darling Basin Governance 1895–1985

The 1895–1902 Federation Drought provided an impetus that brought the colonies/states together to consider how to better manage the River Murray. A major water conference organized in Corowa in 1902 provided the catalyst that eventually resulted in a workable agreement between the states. However, it was not until 1915 that the River Murray Waters Agreement was signed by the governments of Australia, New South Wales, Victoria, and South Australia. It took a further two years to establish the River Murray Commission, which had the task of putting the River Murray Waters Agreement into effect.

In spite of its limitations and even though it marked the minimum upon which formal agreement could be reached, the River Murray Waters Agreement was a pioneering document ahead of its time. The same can be said of the River Murray Commission. Its prime task was the regulation of the main stream of the Murray to ensure that each of the three riparian states, and especially South Australia, received their agreed shares of the Murray's water (MDBC 2007).

The main provisions in the first agreement for the regulation of the River Murray were:

- the construction of a storage on the upper Murray;
- the construction of a storage at Lake Victoria;
- the construction of 26 weirs and locks on the Murray between Blanchetown in South Australia and Echuca in Victoria; and
- the construction of nine weirs and locks on the lower part of either the Darling or Murrumbidgee Rivers (the Murrumbidgee was selected).

Over the 70 years it was in operation, various amendments were made to the River Murray Waters Agreement, reflecting shifts in community values and changes in economic conditions. By no means were all of the changes free of conflict, a comment that also applies to some actions of the Commission, in particular the abandonment of the Chowilla Dam proposal and the construction of Dartmouth Dam. The powers of the River Murray Commission were gradually extended, both by amendment and informal practice, but its prime concern remained with water quantity. The Hume and Dartmouth Dams were built, as were 13 locks and weirs between Blanchetown and Torrumbarry, the Lake Victoria storage, the Maude and Redbank Weirs on the Murrumbidgee, and the Barrages at the Murray Mouth.

In the late 1960s, the River Murray Commission conducted salinity investigations in the Murray Valley. This initiative ultimately led to the further amendment of the River Murray Waters Agreement in 1982 and the broadening of the Commission's role to take account of water quality issues in its water management responsibilities. With the increasing evidence that the successful management of the Basin's river systems was directly related to land use throughout the catchment, further amendments to the Agreement in 1984 enhanced the Commission's environmental responsibilities, but only in a very limited way.

In spite of the changes made to the River Murray Waters Agreement in the early 1980s, it was recognized that the River Murray Waters Agreement and the River Murray Commission were increasingly unable to meet the needs of the Basin's management and its growing resource and environmental problems. This was also a time when important changes were taking place in water resources administration at both state and Commonwealth levels. Further, individual agencies within the separate states were unable to tackle the developing problems of environmental degradation, including such issues as rising water salinity and irrigation-induced land salinization. It was gradually realized that critical issues were no longer confined within distinct jurisdictions, but extended across state boundaries.

These mounting pressures had their outcome in October 1985, when a meeting was held in Adelaide of ministers responsible for land, water and other environmental resources from the governments of New South Wales, Victoria, South Australia and the Commonwealth. The meeting was called to discuss the resource and environmental problems of the Murray-Darling Basin and in particular salinity and land degradation. The meeting was followed by two years of intensive meetings and negotiations by politicians and bureaucrats from the four governments. At both inter-state and intra-state levels, the people involved came to know each other in a way that had never occurred before. The outcome was an agreement between the basin states and the Commonwealth, and involving the community that for the first time took a whole of basin perspective of the water and land resources—the Murray-Darling Basin Agreement. The purpose of the agreement was stated "to promote and co-ordinate effective planning and management for the equitable, efficient and sustainable use of the land, water and other environmental resources of the Murray-Darling Basin."

26.2 The Murray-Darling "Cap" on Water Use

The declining health of the River Murray was acknowledged by the Murray-Darling Basin Ministerial Council in June 1993, when they directed the MDBC to undertake an audit of the water diversions from the rivers of the Murray-Darling Basin. The aim was to determine the rate at which water use was increasing across the basin, to comment on the effects of the increase, and to assess the likelihood and potential impact of future increases.

The audit report revealed unsustainable growth in diversions, which would reduce the security of supply and cause further environmental degradation. The MDBC's modeling showed that, if unchecked, total water diversions could increase by between 7 and 14 % and result in "drought-like" flow conditions in approximately 70 % of years.

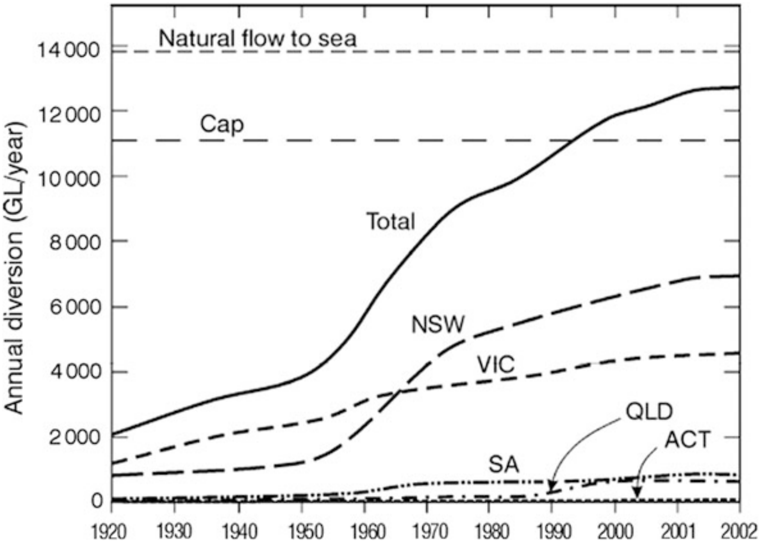

Fig. 26.2 Growth in surface water diversions in the Murray-Darling Basin 1920–2002. *Source* Chartres and Williams (2006)

On the basis of the audit report, the Ministerial Council agreed that a balance must be struck between water for consumptive uses and the riverine environment Fig. 26.2.

In July 1997, the four Murray-Darling states and the federal government signed the agreement to implement the cap, permanently restricting the use of Murray-Darling waters at 1993/1994 levels.

The cap aims to restrain diversions, not development. It states that new developments should be allowed, provided that the water for them is obtained by improving water use efficiency or by purchasing water from existing developments. There is also some scope for use to go up and down each year, depending on climatic conditions.

To address equity issues and for consistency of water management under the cap, the Ministerial Council agreed to six guiding principles:

1. no further change be made to flow regimes that would contribute to further deterioration of water quality and environmental protection (instream, floodplain or estuarine);
2. water allocations be made with extreme sensitivity to the effects on the environment (precautionary principle);
3. water is allocated to the highest value use (allocative efficiency);
4. statutory and agreed property rights be recognized;
5. water management processes be transparent and auditable; and
6. a system of administration be implemented that is easily understood and that minimizes time and costs (administrative efficiency).

While the cap has proven to be effective in the subsequent 15 years at placing a limit on surface water diversions, in hindsight, its scope was insufficient to halt the reduction in water available to the environment. In particular, other activities that impact the basin's water balance including groundwater pumping, construction of farm dams, and plantation forestry have continued to expand, and even accelerate, further reducing runoff and inflows to the Basin's rivers and wetlands.

26.3 Council of Australian Governments Water Reform Framework

In recognition of the pressures facing the Australian water industry and the responsibility of governments to halt the degradation of the environment, the Council of Australian Governments (COAG), made up of the prime minister, state premiers and territory chief ministers agreed on 25 February 1994 to implement a strategic framework of reform to achieve an efficient and sustainable water industry in Australia. The package of reforms agreed to by COAG involved:

- pricing based on the principles of full-cost recovery and transparency or removal of cross-subsidies;
- future investment in new schemes, or extensions to existing schemes, to be undertaken only after appraisal indicated it is economically viable and ecologically sustainable;
- comprehensive systems of water allocations or entitlement, backed by separation of water property rights from land title and clear separation of entitlements in terms of ownership, volume, reliability, transferability and, if appropriate, quality;
- formal determination of water allocations or entitlements, including allocations for the environment as a legitimate user of water;
- trading, including cross-border sales of water allocations or entitlements, within the social, physical and ecological constraints of catchments;
- administration and decision making to provide an integrated catchment management approach to water resource management;
- the separation of resource management, standard setting and regulatory roles of government from the roles of providing water services;
- a greater degree of responsibility for local management of water use;
- public education about water use and consultation in implementing the water reforms;
- appropriate water-related research and use of efficient technologies.

The implementation of the 1994 Framework Agreement was tied to the National Competition Policy in April 1995 when COAG agreed to make incentive payments to states based on degree of compliance with the Commonwealth's National Competition Policy water policy goals. This incentive linkage of the competition and water policy reforms gave impetus to the state's efforts to achieve key elements of these reforms. However, by 2003, the pressure was mounting for a renewal of the water reform agenda, driven in large part by the increasing grip of drought on southern and eastern Australia and many of Australia's state capital cities (Gardner et al. 2009).

26.4 Australia's Millennium Drought 1996–2009

Over the last decade, much of southern Australia and coastal Queensland has experienced a protracted downturn in annual rainfall, which intensified after the 2002 El Nino event, and most severely affected the eastern states and the southwest corner of Western Australia (Fig. 26.3 left-hand side). A second more widespread downturn in annual rainfall started during the 2002 El Niño event. It most severely affected the eastern states (Fig. 26.3 right-hand side).

The low rainfall during 1997, 2002 and 2006, contributing to the long-term drought, can be understood in terms of the El Niño events that occurred during these years. Earlier El Niño events were commonly followed by good drought-breaking rains. However, rainfall in the years following the 2002 event was insufficient to fully alleviate the rainfall deficiencies. This is reflected in the very low levels of water stored in eastern Australia's large dams in the late 2000s.

In the southwestern portion of Western Australia low autumn/winter rainfall exacerbated the long-term decline in water availability which commenced in the 1970s. Research suggests this long-term decline was due partly to the effects of global climate change as well as to natural climate variability (NWC 2006).

The impact of the drought since 1997 is apparent in the reduced inflows to major water storages across many areas of Australia, in particular the eastern states and the southwestern portion of Western Australia. The significant reduction in storage inflows in Perth since the 1970s is acknowledged as being a step change in climatic conditions. Rainfall in the Perth region decreased by 14 % and runoff by 48 % between 1975 and 1996 (CSIRO 2005) Fig. 26.4.

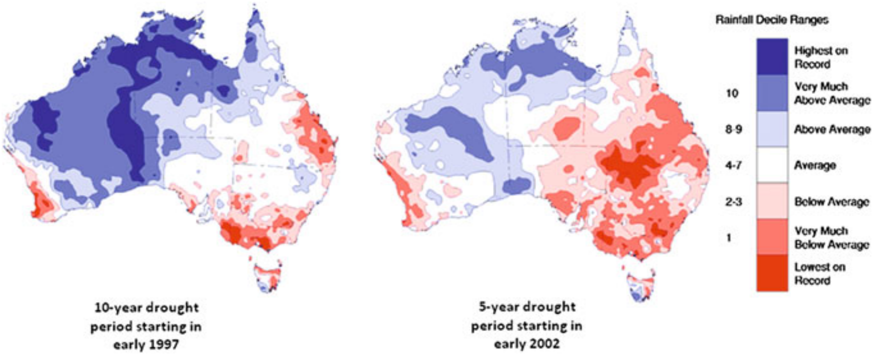

Fig. 26.3 Rainfall deciles showing above- and below-average rainfall up to October 2006. *Source* Bureau of Meteorology, NWC 2006

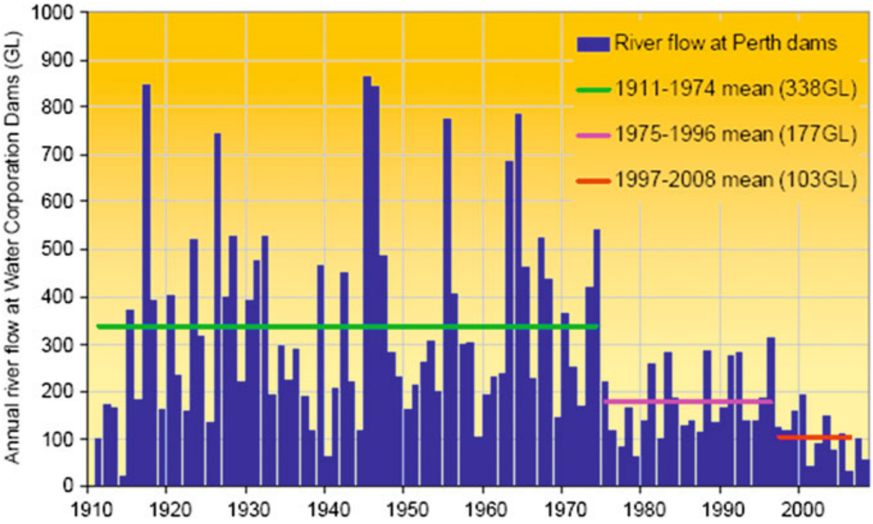

Fig. 26.4 Annual inflows to Perth storages. *Source* Ruprecht (2009)

Recent planning in Victoria for the central Region Sustainable Water Strategy similarly acknowledges that a step change may have occurred since 1997 in that region. The inflows into the Canberra storages declined steadily since the mid-1990s until 2010; however, these low inflows in recent years are not the lowest on record as similarly low inflows have occurred a few times since 1880 (NWC 2007b).

The problem with the recent drought and low flows is that over the last 100 years, development of the resource has occurred during wetter periods and so many more users are now reliant on the water resource than in previous droughts.

26.5 Water Reform Outcomes of the Millennium Drought

26.5.1 Australia's National Water Initiative

In the context of the recent drought, at the August 2003 meeting of COAG, it was agreed that there was a pressing need to consolidate and refresh the 1994 water reform agenda to increase the productivity and efficiency of water use, sustain rural and urban communities, and to ensure the health of river and groundwater systems. COAG agreed to develop a National Water Initiative (NWI).

The NWI represents a shared commitment by governments to increase the efficiency of Australia's water use, leading to greater certainty for investment and productivity, for rural and urban communities, and for the environment.

The overall objective of the National Water Initiative is to achieve a nationally compatible market, regulatory and planning-based system of managing surface and groundwater resources for rural and urban use that optimizes the value of water to Australia considering economic, social and environmental outcomes. At the highest level, implementation of the National Water Initiative is aiming to achieve:

1. clear and nationally-compatible characteristics for secure water access entitlements;
2. transparent, statutory-based water planning;
3. statutory provision for environmental and other public benefit outcomes, and improved environmental management practices;
4. complete the return of all currently over-allocated or overused systems to environmentally sustainable levels of extraction;
5. progressive removal of barriers to trade in water and meeting other requirements to facilitate the broadening and deepening of the water market, with the implementation of an open trading market;
6. clarity around the assignment of risk arising from future changes in the availability of water for the consumptive pool;
7. water accounting that is able to meet the information needs of different water systems with respect to planning, monitoring, trading, environmental management and on-farm management;
8. policy-settings that facilitate water use efficiency and innovation in urban and rural areas;
9. addressing future adjustment issues that may impact water users and communities; and
10. recognition of the connectivity between surface and groundwater resources and connected systems managed as a single resource.

As signatories to the National Water Initiative (NWI), all state and territory governments were required to lodge plans for how they will implement the requirements of the NWI. These plans, which are accredited by the National Water Commission, include actions and timelines for implementation of key actions under the NWI, and highlight a number of areas in which jurisdictions needed to further develop their water management arrangements to meet the requirements of the NWI.

Implementation of the NWI was supported by the Australian government's Raising National Water Standards Program. This $250 million program offered support for projects to improve Australia's national capacity to measure, monitor and manage its water resources. Funds from the Raising National Water Standards Program were directed at activities across three strategic investment areas:

1. advancing the implementation of the National Water Initiative;
2. improving integrated water management across Australia; and
3. improving knowledge and understanding of our water resources.

In 2007, the $105 million National Groundwater Action Plan was initiated by the Commission under the Raising National Water Standards Program to fund projects to progress the groundwater reforms agreed to under the National Water Initiative.

26.5.2 The National Plan for Water Security

When the NWI was signed in 2004, it appeared that the grip of drought may have been easing, However, 2006 saw an unexpected and severe intensification of drought conditions in many of the state capital cities and the Murray-Darling Basin.

A Water Summit called by the then Prime Minister John Howard to consider an emergency response to the drought in November 2006 led to the 2007 National Plan for Water Security to provide a further major reform of Australian water management. The proposed plan included unprecedented funding of $10 billion over 10 years, with $5.8 billion for water-use efficiency investments and $3.1 billion for water-entitlement buyback, along with a 10-point plan to improve water efficiency and address over-allocation of water in rural Australia.

A major condition of the proposed plan and point of controversy was a proposed full referral of water management powers for the Murray-Darling Basin (Clause 100 of the Constitution) from the states to the Commonwealth. To the surprise of some in the water industry, New South Wales immediately agreed to the referral of powers, with South Australia and Queensland soon following New South Wales lead.

Despite the support of the other states, Victoria, which considered itself to be the leading jurisdiction in water management, opposed the referral of powers and with strong support from the Victorian Farmers Federation, dug its heels into oppose the Federal government's plan. Following several months of negotiations between the federal and Victorian governments, by mid 2007 it was obvious that a deal would not be reached in the foreseeable future and the federal government decided to legislate for a more modest reform agenda that retained the $10 billion investment but involved a more limited federal take over of water management authority based on its existing powers and bringing Victoria into the agreement, hence creating the Commonwealth Water Act.

26.5.3 Water Legislation—Commonwealth Water Act (2007)

The key features of the Water Act 2007 are:

- The Act establishes the Murray-Darling Basin Authority (MDBA) with the functions and powers, including enforcement powers, needed to ensure that Basin water resources are managed in an integrated and sustainable way.

- The Act requires the MDBA to prepare the Basin Plan—a strategic plan for the integrated and sustainable management of water resources in the Murray-Darling Basin.
- The Act establishes a Commonwealth Environmental Water Holder to manage the Commonwealth's environmental water to protect and restore the environmental assets of the Murray-Darling Basin, and outside the Basin where the Commonwealth owns water.
- The Act provides the Australian Competition and Consumer Commission (ACCC) with a key role in developing and enforcing water charge and water market rules along the lines agreed in the National Water Initiative.
- The Act gives the Bureau of Meteorology water information functions that are in addition to its existing functions under the Meteorology Act 1955.

26.5.4 Murray-Darling Basin Authority

The Water Act of 2007 established an independent Murray-Darling Basin Authority (MDBA) with the functions and powers, including enforcement powers, needed to ensure that Basin water resources are managed in an integrated and sustainable way. The MDBA will oversee water planning considering the Basin as a whole, rather than state by state, for the first time.

Key functions of the MDBA include:

- preparing a Basin Plan for adoption by the minister, including setting sustainable limits on water that can be taken from surface and groundwater systems across the Basin;
- advising the minister on the accreditation of state water resource plans;
- developing a water rights information service which facilitates water trading across the Murray-Darling Basin;
- measuring and monitoring water resources in the Basin;
- gathering information and undertaking research;
- engaging the community in the management of the Basin's resources; and
- providing independent advice to the Commonwealth Minister for Water.

26.5.5 The Murray-Darling Basin Plan

The Water Act requires the MDBA to prepare a strategic plan for the integrated and sustainable management of water resources in the Murray-Darling Basin. This plan is referred to as the Basin Plan. The Act establishes mandatory content for the Basin Plan, including:

- limits on the amount of water (both surface and ground water) that can be taken from Basin water resources on a sustainable basis—known as long-term average

sustainable diversion limits. These limits will be set for Basin water resources as a whole and for individual water resources;
- identification of risks to Basin water resources, such as climate change, and strategies to manage those risks;
- requirements that a state water resource plan will need to comply with if it is to be accredited under the Water Act;
- an environmental watering plan to optimize environmental outcomes for the Basin by specifying environmental objectives, watering priorities and targets for Basin water resources;
- a water-quality and salinity management plan which may include targets; and
- rules about trading of water rights in relation to Basin water resources.

The Basin Plan will be complemented through water resource plans prepared by Basin states and provided to the Australian government minister for accreditation. The MDBA will provide advice to the minister on whether to accredit such plans. Water resource plans will only be accredited if they are consistent with the Basin Plan, including the long-term average sustainable diversion limits.

26.6 Current Status of Australian Water Reform and Future Directions

One of the main roles of the National Water Commission is as Australia's independent auditor of water reform progress. The Commission undertakes biennial assessments, with the two-yearly reports provided to COAG as a report card of progress in water reform and as an aid to maintain and focus ongoing reform efforts.

The Commission's 2009 biennial assessment "Australian water reform 2009" was released on 9 October 2009 and considered by COAG at its December 2009 meeting (NWC 2009). The report is the product of a 12 month process involving significant consultation and contains more than 100 findings and makes 68 recommendations.

The report acknowledges that as a result of Australia's agreed water reform framework, the National Water Initiative, water reform is going better than it would otherwise, in tough conditions:

- There is unprecedented attention to water, coupled with unprecedented budgets especially the $12.9 billion "Water for the Future" Program on the part of the Australian government.
- Water trading has proven to be very successful and is applauded internationally.
- Progress has been made in supplementing and diversifying urban water supplies.
- The report welcomes historic governance reforms in Murray-Darling Basin.
- Buybacks for the environment are a commendable development.

However, the assessment found that over-allocation of water systems, has yet to be fully addressed, even though it's now been more than 15 years since state governments first promised to fix it as part of the 1994 COAG water reforms. Significant areas for ongoing effort and improved action are highlighted

- 40 % of promised water plans are still outstanding, and many others are suspended—caught short by climate change.
- There is ample evidence of environmental degradation, yet the aims and results of some environmental watering are still unclear.
- Barriers to water trade are still being imposed by state governments.
- Irrigators lack the information, clarity and therefore confidence they need for planning and investment decisions.
- Interstate bickering over water continues, intergovernmental processes are slow, and states lack adequate policy and implementation resources.
- Meanwhile, climate change has raised the bar on water reform—making the challenges even more urgent than previously thought.

26.7 Conclusion

Drought is an ongoing feature of Australian life and has profoundly influenced the Australian psyche. Numerous droughts have occurred in the 220-odd years since European settlement; however, due to their severity and the combination of climatic, hydrologic and political events the 1895–1902 Federation and 1997–2009 Millennium droughts have proven to be the most influential on Australian water policy.

Despite significant rainfall in 2010 and 2011, ending the Millennium drought, Australia's water resources will undoubtedly be subject to ongoing climate variability and change in the future. Renewed reform momentum is now urgently needed. The National Water Initiative, and the new MDB plan are the primary Commonwealth and state government initiatives that set broad directions for Australian water policy. If the Commonwealth and partner state governments fully and expediently follow through on the detail of implementation, Australia may prove successful in managing its water for irrigators, cities, industry, and the environment.

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Part VI
Conclusion

Chapter 27
Summaries and Considerations

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Abstract With future drought events expected to become both more frequent and intense in semi-arid and arid regions worldwide, a better understanding of the potential impacts and drivers of drought along with informed insight into the potential effectiveness of various strategies for addressing drought becomes increasingly valuable. To help promote a better understanding of these impacts, drivers, and strategies from a multinational and multidisciplinary perspective, this chapter summarizes the salient themes from each of the five disciplinary sections in this book.

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27.1 Introduction

A consistent theme across the five sections in this book is the expectation of more frequent and intense droughts with increasing water demand and periodic dry spells accentuated under climate change. While damages from drought are unavoidable, the degree of damage is not only a function of the resilience in the natural system and the level of water stress associated with any particular region's water resources system, it is also a function of our *knowledge* of these systems. Broader understanding of how these systems operate and are impacted can condition the coping and mitigation strategies society develops and implements. While a single region or country's historical experience with drought can inform their expectations and preparedness for future drought, in a world of rapidly evolving water demand and climate change this may offer limited perspective for managing future drought. As Dreverman notes in Chap. 26, the historic record of drought may no longer be a reliable indicator of what to expect in the future. Hence, a goal of this book was to increase our knowledge of drought, its impacts on natural and man-made systems, and potential strategies for effectively addressing drought by highlighting the experiences, strategies, and scientific research associated with drought in a number of countries that contain sizeable semi-arid or arid regions. With this goal in mind, the next five sections will summarize the salient points from each of the major disciplines represented in this book.

27.2 Summary of Agronomy, Irrigation Technology, and Water Supply

This section summarizes the Section 1 discussion of the technological and agronomic aspects of drought response in irrigated agricultural regions and municipalities in Australia, Spain, South Africa, and the United States. Not surprisingly, these case studies present many differences. One of the more obvious contrasts is the scale of operation of irrigation across countries ranging from subsistence maize (corn) farming in South Africa, with small holder farms in Spain and South Africa, and larger commercial farms in the United States and Australia. In Spain and South Africa, both small holder and large commercial farms are present and this presents a unique set of challenges. Another contrast is the history of irrigation and irrigation policy in the old world region of Spain which predates the first irrigation infrastructure built in the Murray Darling Basin of Australia by centuries. Despite these differences, there are many common aspects relating to how these regions approach increasing and/or extending scarce water supplies. Table 27.1 summarizes actions taken within each country in response to drought discussed in this book.

Table 27.1 Summary of water management strategies for increasing and extending the available water supply from Section 1

Action	Australian case study (Chaps. 3 and 5)	South African case study (Chap. 8)	Spanish case study (Chaps. 4 and 6)	U.S. case study (Chaps. 2 and 7)
Increase supply				
Increase storage capacity				
Reservoirs	x			
Alternate supplies				
Municipal water	x			
Desalinization	x			
Wastewater	x			
River	x			
Groundwater	x			
Rain	x			
Agricultural water				
Desalinization			x	
Wastewater			x	x
Groundwater			x	x
River	x		x	
Extend supply				
Infrastructure				
Water meters			x	
Canal lining			x	
Pressurized systems	x	x	x	x
Technology				
Scientific irrigation scheduling	x	x	x	x
District management software			x	
Improved irrigation system operation	x	x	x	x

(continued)

Table 27.1 (continued)

Action	Australian case study (Chaps. 3 and 5)	South African case study (Chap. 8)	Spanish case study (Chaps. 4 and 6)	U.S. case study (Chaps. 2 and 7)
Management				
Modified cropping patterns	x	x	x	x
Crop selection	x	x	x	x
Cultivar selection		x		
Soil management	x	x		x
Deficit irrigation	x		x	x
Set yield targets		x		
Include rainfall in supply	x	x		x
Canopy management (pruning)	x			x

27.2.1 Increase Supply

Options for increasing the total water supply include construction of reservoirs, desalinization of saline water (ocean, saline drainage water), reusing treated wastewater, drilling new wells into aquifers, and abstraction from rivers. While these options are available both to municipal and agricultural users, the cost of these options varies widely and may be prohibitive for agriculture compared to municipal supply. The option of construction of reservoirs is limited by silting and available runoff to fill the reservoirs. Most of the cost effective and viable sites for reservoirs have been identified and used, and the remaining sites are not cost effective. Furthermore, environmental concerns and restrictions have severely limited the potential for additional reservoir construction throughout the world.

Desalinization of ocean water is an expensive and energy intensive option that is available to municipalities because the cost can be passed on to the consumer. This is one option selected by the government in Adelaide, Australia as part of its strategy to increase water supply and be independent of rainfall and competing water users in the Murray Darling Basin. The environmental concerns with desalinization relate to the disposal of the brine and the energy used in the process. Desalinization is generally not an available option for agriculture because of the high cost of water along with the volume of water required for production. Furthermore, in many cases extensive irrigated agriculture is far from the coast. Agricultural operators have investigated in the use of smaller scale desalinization of ground or surface water with salt content significantly lower than the ocean and these processes appear to be economically viable in some cases.

Treated municipal wastewater has become a viable option for both municipal and agricultural uses. Tertiary treated wastewater is being used for groundwater recharge and subsequently municipal water supply since direct use for secondary treated wastewater can be used in municipalities to irrigate landscapes and other non-potable uses. Secondary, and in some cases tertiary (e.g., Spain), treated wastewater has become a source of water for irrigated agriculture adjacent to large municipalities. Secondary treated wastewater is also being used for groundwater recharge to replenish aquifer systems used for irrigated agriculture. Given the rate of urban population growth in all countries, this source of water is likely to increase. In addition to managing the buildup of salts and nutrients in irrigated soils, there is a challenge of moving water from the source to the end use as the energy cost of pumping water can be excessive.

Drilling new wells into existing aquifer systems will provide additional water supply but there are limits to the extent this can be performed from a sustainability perspective. There are also considerations for the quality of the groundwater and its suitability for long-term agricultural production.

Rivers also provide an opportunity to increase the total water supply. This was one strategy developed in South Australia to cope with increased demand. However, there are limits to the total available water from a river system. These limits are set by the total runoff from the watershed and the existing water rights for agriculture and other municipalities in the watershed. This also creates the conflict between which use has the higher right to water. This is apparent for the environment, irrigators, and consumers in South Australia located at the downstream end of an over allocated and variable water resource.

Rainwater collected from rooftops has been used to extend the available water in Adelaide. This is a common technique used throughout Australia to augment water supplies in rural areas as well as large cities. This method is most effective in regions with rainfall throughout the year. Mediterranean climates such as Adelaide's with wet winters and hot dry summers mean that tanks have to be large to be effective if they are to be used for gardens through the summer.

27.2.2 Water Conservation and Demand Management

Upgrading and improving the existing infrastructure is a simple method available to both irrigated agriculture and municipal water supplies. This includes improving pipelines and lining canals that are transporting water. The installation of water metering provides opportunities for improved water management both in agriculture and cities. In cities, the adoption of low flow showers and toilets has been a successful way of extending the available water supply.

Switching from surface irrigation to pressurized systems such as sprinklers and micro irrigation was a common theme across all of the countries discussed in this book. Pressurized systems enable a reasonably uniform distribution of water across a field and good control on the depth of application compared to surface irrigation. This results in less deep percolation losses. In most cases yields are increased due to better targeting of plant water requirements, higher frequency of irrigation and less waterlogging. Not only are yields increased but there is better access to the field for pest control, fertilizing and harvesting.

The major limitation is the cost associated with installation of pressurized systems. This may be offset by significant yield increases but in some cases the change in irrigation system requires a change in the crop being grown to support the additional cost. For this transition to be successful, a farmer will have to modify existing irrigation practices, and water will have to be available on demand. Pressurized systems are generally linked to groundwater, and pressurized delivery systems in a canal system will require on-farm storage.

Improving the irrigation system operation is a crucial step in extending the water supply. This involves both pressurized and gravity-fed systems such as furrow, basin, and border. Improvements include laser leveling to establish proper grades, adjusting field length, establishing proper flow for basin size and developing tailwater return systems. For pressurized systems, improving operations include maintaining sprinkler and nozzles, and ensuring correct design of lateral lengths and operating pressures. The impact of these steps will be to improve the distribution uniformity throughout the field which will reduce the deep percolation losses. Pressurized systems will provide improved control on the depth of application compared to gravity systems.

Management options provide easy alternatives for extending water supplies without incurring large upfront costs associated with changing or upgrading irrigation systems. Most of the management alternatives were related to the agronomic side of production. A simple first step is to modify the existing cropping pattern to select crops with lower water requirements. Another easy decision is whether to grow a crop or not in a given year which is obviously an option available to annual cropping. In the case of perennial crops, a combination of low water supply and low commodity prices can lead to irrigators applying a minimum maintenance supply for their vines or trees.

Crop selection includes consideration for the salt tolerance and total growing season. Salt tolerant crops then can be grown with higher salinity waters thus extending the existing good quality water supply for salt sensitive crops. The length of growing season has a significant impact on crop water use. Cotton being grown throughout the summer months has a significantly higher crop water requirement than a fast growing crop such as lettuce grown in the fall and spring. Cropping at different times of the year will enable the crop to take advantage of rainfall. This is particularly true in regions with strong seasonality of rainfall such as the Central Valley of California. In addition to changing crops, changing cultivars of specific crops given their different water requirements and salinity tolerances also may be an option to extend supply.

Soil management is another agronomic practice requiring little expense. In this case, the soil surface is managed to create mulch that reduces soil water evaporation and improve infiltration. Practices that have been developed for water conservation in dryland agriculture can be implemented in irrigated agriculture as well to improve the total annual water supply. These practices have been widely used in South Africa and are beginning to be used in California. Conservation tillage that includes keeping stubble in place to improve infiltration and managing weed growth are also alternatives included in dryland agriculture.

Adoption of scientific irrigation scheduling methodology is a common theme for each of the countries providing data. This involves determining the crop-water requirement and establishing the depth and time of application based on the available stored soil water and the rate of crop water use. Determining the crop water use can be done using soil water measurements, daily estimates of ET_o from newspapers, access to weather station data, and remotely sensed data. Irrigation scheduling provides a method to better match the crop water requirement and depth of applied water, thus resulting in reduced stress and reduced deep percolation losses.

Use of irrigation scheduling methodologies can be done at the farm level but often is a service provided at the district level. Use of this technology along with scheduling of water supply throughout the distribution system will improve the overall management of the district and enable the on-demand supply of water. Several irrigation districts in Spain developed district-wide management software to facilitate the system operation. This included some irrigation scheduling on farm as well as including tracking of applied water for billing purposes.

Deficit irrigation strategies are also commonly used in irrigated agriculture. Commonly used methods include regulated deficit irrigation (RDI) and partial root zone drying (PRD). Two strategies can be developed for RDI. In the first strategy there is a uniform reduction of irrigation throughout the entire growing season. This has been implemented in some cases very successfully. The implication would be that the crop-water requirement is not well defined, such that reduced irrigation does not result in a negative impact on crop yield. In the second strategy the irrigation deficits are applied at strategic physiological growth stages that are known not to impact yield. Those sensitive growth stages then are fully irrigated. For early season crops it is possible to develop strategies to deficit irrigate following harvest with no significant impact on the subsequent years yields.

The partial root zone drying concept involves alternating irrigation to the crop root zone to induce stress in part of the plant but not the whole plant. This results in a reduction of total transpiration, but does not have a significant negative impact on yield. The downside of this strategy is the requirement to have a second irrigation system within the orchard or vineyard which adds considerably to the expense. Research has questioned how the water savings and quality improvements from this strategy differ from a simple RDI strategy with a uniform reduced depth of application.

Any deficit irrigation strategy requires a detailed knowledge of crop physiology and yield responses to ensure minimal impact on yield. As deficit irrigation is generally practiced on perennial crops the impact on yield is especially complex. This also means there is very little margin for error in the management of the irrigation system. There are still large gaps in knowledge about plant responses to deficit irrigation for a wide range of crops, including the question of the long term impacts of deficit irrigation on perennial crops.

Pruning strategies have been developed for perennial crops to reduce the total transpiration. This has been practiced in Australia and the United States. The impact may be a loss of the crop output for several years but not the loss of the plant.

A strategy developed in South Africa sets yield targets for individual annual crops based on available and expected water supply. These targets then can be managed by varying the crop planting density and the cultivars being used. This requires a detailed knowledge of the rainfall and stored soil water prior to planting. This is an effective way of including rainfall in the total water supply.

27.2.3 Concluding Remarks

These different case studies highlight the many engineering and agronomic opportunities to improve the management of water on farms and in municipalities. The effectiveness of a strategy will vary across crop type, soil type, and municipal setting. While these ideas can be transported from one location to another, investments will be needed for local adaptation and fine tuning. It is also important to note that there are limits to the extent of efficiency gains from engineering and agronomic management.

Policy makers should also be aware of the law of unintended consequences. An interesting example is the discussion of irrigation modernization in the Ebro valley in Spain which will improve drought management at the farm scale. Better irrigation systems are likely to lead to more irrigation and, consequently, basin water use is likely to increase. Hence, irrigation modernization can contribute to water scarcity and watershed closure. Another unintended consequence of improvements in irrigation efficiency in Australia has been the problem of rootzone salinity due to eliminating leaching. This reminds irrigators of what ecologists have long known about trades-offs between efficiency and resilience. There are many gains to be made in smarter water management in agronomy, irrigation technology and water supply. However, some of the gains in efficiency such as minimizing loss of water below the rootzone or lining canals can be illusionary as this water that was 'lost' at one point was actually returning to the river or aquifer.

Despite the many challenges, an encouraging aspect of all the case studies was the reference to learning from recent droughts. The value in documenting these case studies from contrasting regions lies both in the ability to learn from the success and mistakes in one's own region as well as the success and mistakes in other regions.

27.3 Summary of *Ecological Impacts of Drought*

This section compares responses of several Mediterranean and subtropical ecosystems to drought and water scarcity. While the considered ecosystems cover a wide range of semi-arid regions around the world with different regional features and levels of human intervention (see Table 27.2), they all are sensitive to the effects of water stress due to a combination of strong natural variability, human overexploitation of water resources and decreasing availability due to climate change.

27.3.1 Drought-Related Consequences on Ecosystem Functioning and Services

From the analysis of the case studies we conclude that all of the regions discussed suffer from increasing water scarcity. The root of the problem is the increasing water demand for human uses combined with the decreasing water availability due to climate change and pollution. This scenario is leading to extended and more frequent periods of water stress impacting ecosystems in a number of ways, putting them at risk of irreversible changes and diminished capacity to provide ecosystem services for humans.

Table 27.2 Summary of the main features of the case studies considered to analyze the impacts of drought and water scarcity on semi-arid ecosystems from Section 2

Region	Iberian peninsula	Southwestern US	Cuatrociénagas valley	Murray-darling basin
Country	Spain and Portugal	United States	Mexico	Australia
Surface (km^2)	583,000	1,810,509	8,000	1,061,000
Population	52,353,914	56,198,784	12,220	2,004,560 (within basin, more outside basin reliant on basin resources)
Main water uses	Agriculture (68 % Spain, 48 % Portugal)	Agriculture (72 %, Colorado Basin)	Agriculture (>90 %)	Agriculture (>90 %)
Analyzed ecosystems	Rivers, estuaries, lakes and wetlands	Terrestrial ecosystems	Lakes and wetlands in the Chihuahuan deserts	Rivers, estuaries, lakes and wetlands
Most impacted ecosystems	Southern rivers wetlands (e.g., Tablas de Daimiel)	Forests and grasslands	Chirunce system (aquatic, riparian and xeric flora and fauna)	River red gum forests The Coorong and Lower Lakes
Main system responses	Invasive species widespread severe wetland degradation	Widespread tree mortality shifts in community structure	Hydrological system alteration widespread sinkhole formation	Riparian forest die-off loss of aquatic communities loss of estuarine conditions

Ecological theory predicts that rapid and large changes in ecosystem structure and function will occur more frequently in the future under such increased water stress. In combination with other human impacts and natural disturbances, an increase in the rate of nonlinear change and a decrease in resilience are predicted (Smith et al. 2009; Scheffer et al. 2001).

Most of the freshwater ecosystems in semi-arid regions are particularly vulnerable, due to the intense, frequent and synergetic effects of natural and human-induced disturbances. Looking at the studied cases, the main observed responses of the aquatic ecosystems to increasing water stress are the loss of ecosystem integrity (e.g., lagoon drying, riparian forest die-off, salt stress in wetlands), the alteration of its functionality (e.g., population declines, reduction in species richness, increasing presence of invasive species) and the reduction of ecosystem services (e.g., high quality water for human uses, recreational values, fishing). A review of 50 papers (Matthews and Marsh-Matthews 2003) found that the most frequently demonstrated effects of drought on fish were population declines, loss of habitat, changes in the community, negative effects from changes in water quality, movement within catchments, and crowding of fish in reduced microhabitats.

In terrestrial ecosystems the production of nearly all ecosystem services will be reduced in response to drought through reduced biological functioning. At the physiological level, reduced water availability can lead to stomatal closure and a reduced capacity to uptake CO_2. This can lead to reduced plant production of material goods, carbon sequestration, and other services. In combination with increasing temperatures and changes to atmospheric chemistry, several unexpected ecological responses are occurring in forests. The most recent drought in SW United States, circa 2000, was associated with a relatively new ecological response of widespread tree mortality, which had not been observed in prior droughts (Breshears et al. 2005). While not a clear indication of drought due to climate change, this event is an example of the consequences of such climate change-induced droughts (Adams et al. 2009). Occurrences of widespread tree mortality have become more common throughout the world (Allen et al. 2010). This observation has led to debate over the causes and implications of widespread mortality phenomenon for understanding ecosystem functioning in response to likely future drought.

27.3.2 Concluding Remarks

In order to prevent further severe damages in ecosystems and the loss of ecosystem services, water policy must quickly shift towards a demand-management and ecosystem-oriented approach, aiming to reduce the total water use, increase its efficiency, and restore aquatic ecosystems. One of the main measures to be urgently implemented for mitigating the effects of water scarcity in aquatic ecosystems is the establishment and implementation of a pulsing environmental flow regime, designed to maintain crucial ecological functions and biodiversity.

Future research should focus on quantifying the ecological effects of water scarcity at different spatial and temporal scales (both in terrestrial and aquatic ecosystems), developing specific ecological indicators of water stress, and also on determining and modeling the influence of altered river flows and rainfall patterns in maintaining biodiversity and ecosystem functions and services.

27.4 Summary of Hydrology and Water Resource Systems

In the interests of clarity, it is useful to draw distinctions between three concepts—aridity, water scarcity, and drought—from a hydrological perspective.

Aridity is a characteristic related to the climate of a specific region, and can be defined as the ratio of average precipitation over average potential evapotranspiration (ETP). Low values of this index correspond to more arid regions, and higher values correspond to more humid regions (UNEP 1992). The metric is convenient as it only requires an average value of precipitation and potential ETP. However, temporal dimensions of drought are not well described by this index. Aridity indexes can be computed in a spatially distributed way; as such, large areas, like Australia, United States, South Africa, México, or even Spain (and California), which include different regions with differing levels of aridity, can all have different indices.

Section 3 of this book discusses how water scarcity relates to the availability of water for human activities. One index of such scarcity is per capita water availability, computed as the value of average renewable resources available divided by the population (expressed in m^3 per capita). Another index used in the introduction of this book—the water exploitation index—is the ratio of water demand over the average renewable resources in some regions of the world. Population (and hence, water demand) increases have large impacts on water availability for human uses. For example, in Mexico, per capita availability has fallen by 75 % in 60 years. Sometimes, these types of statistics are misleading as they confuse population, water resources, and climate change problems. In fact, in many arid regions water demand growth from population doubling almost every 30–50 years will be confounded by climate change induced rises in water shortage (Kummu 2010).

The concept of drought, in contrast with aridity and scarcity, has a fundamental time dimension, as drought is generally defined as a period of below normal water availability. Thus drought can occur in arid or humid regions. Characteristics of droughts are different within regions, depending on statistical characteristics such as frequency, intensity and duration of below normal water availability. Arid and semi-arid regions, like those considered in this book, are distinguished by long duration (up to several years), and high intensity droughts.

A commonly used definition of drought relates to below average precipitation (meteorological drought). The impacts of meteorological drought depend on spatially varying soil moisture holding capacity and vegetation characteristics. Meteorological drought is transformed by nature into hydrological drought, below normal flows in rivers and springs, below normal storage in natural lakes and aquifers. This can affect riparian vegetation and ecosystems related to river, springs, lakes, or wetlands environments.

Human dimensions of drought are introduced when any type of the previously mentioned droughts affects human activities. As a consequence of soil moisture drought, a rain-fed agricultural drought can develop; and, as a consequence of hydrological drought, a water supply drought can develop (affecting irrigated agriculture and/or urban supply, among others), or other types of drought depending on the activity sector affected (for instance, a “navigation drought” as occurred in the Murray-Darling Basin).

27.4.1 The Benefits of Developing Water Resource Systems for Drought Planning

One common feature of the cases of study in Section 3 is that in response to past drought events, water infrastructure has been developed to provide more reliable supply and a reduction in vulnerability for the water dependent activities. The result is a water resource system (WRS) whose yields and performance depend not only on hydrology, but also on infrastructure and management.

When a WRS cannot provide all water services to the extent normally provided, the result is a WRS drought (or operational drought). All papers in Section 3 deal mainly with WRS, where water scarcity and droughts affect irrigated agriculture, urban and industrial water supply, hydroelectricity production, and navigation, among other activities. It is also noted in several chapters that in most WRS, water scarcity and droughts have disproportionate impacts on the water environment including greater losses in water quantity and water quality for ecosystems than for consumptive water uses.

A common conclusion in all the chapters is that WRS, in arid or semi-arid regions with water scarcity and prone to hydrological droughts, must be designed and managed with the permanent objective of preparedness for drought anticipation and mitigation; that is, with a proactive approach rather that the classical reactive approach.

To be effective, drought planning and management (DPM) requires a sound scientific understanding of the physical components and hydrological processes of the WRS (e.g., precipitation-runoff processes, including aquifer recharge and functioning, as well as surface–groundwater interactions), the human components (e.g., water demands, infrastructure, water rights, priorities, etc.), and the environmental components (e.g., ecosystems requirements and dynamics, tolerable low flows and water quality). Models to assess the effect of any action on future WRS performance are useful in this regard when they account for the interrelationships between different components in an integrated manner.

Knowledge of historical droughts is recommended since it can help in the design of infrastructure and management of WRS for future droughts. Nevertheless, droughts differ in their temporal and spatial characteristics; consequently, mitigation measures derived from the learning process by the analysis of past droughts will have to be tailored to the real time situation. Moreover, as depicted in many of the chapters in this section, it is very likely that in arid and semi-arid regions, climate change, besides increasing water scarcity in general terms, will exacerbate meteorological and hydrological drought spatially and temporally, including changes in seasonal distribution of water stress, thereby producing more frequent and more intense droughts with longer duration. So, plans for drought will need to be updated constantly, and WRS will need to be adapted for new situations, as seen in some of the chapters of Section 3.

One of the most important steps in DPM is the selection and establishment of adequate drought monitoring systems. There exist many types of drought indexes, among which the SPI index (McKee et al. 1993) is the most famous nowadays for meteorological drought. But for each type of drought mentioned above, specific indexes have been developed, or adapted from previous ones. Moreover, for every region or basin, some indexes describe the actual situation and the impact of drought on different sectors better than others. This is why it is essential that different types of indexes be analyzed in order to find the most adequate for the case of interest, and to provide a realistic view of the situation. In some cases, as shown in the Jucar River Basin case study in Spain, the analysis led to the development of a specific index for WRS drought (or operational drought, as called in the chapter) which takes into account several meteorological and hydrological variables, including storage in reservoirs and aquifer levels, and also acknowledges impacts on different sectors. As such, the index allowed one to correlate statistically the relationship between the values of the index and the severity of the drought situation. In order to compute the values of the indexes in a distributed way within the region or basin, it is essential to have accurate and up-to-date meteorological–hydrological observations and an elaborate monitoring system with real time data acquisition. Furthermore, communication links between the monitoring systems to the institution(s) were the index is computed and displayed for decision makers and the public on a regular basis (for arid and semiarid regions monthly basis can be adequate) is required.

In Table 27.3, a summary of the particular circumstances of each case study with respect to the issues raised in this section can be found. A number of drought mitigation and coping measures are identified. One measure noticeably absent is drought insurance, which can be very effective as a coping measure given the success such a measure has achieved in Spain. Of course, the right combination of these measures will depend on the drought situation as well as on the legal, social, institutional conditions in every place (WRS).

Table 27.3 Summary of the main features of cases studies in Section 3

Name of the case of study in Section 3	Spain	Australia	South Africa	Mexico	United States of America
	Jucar River Basin	Murray-Darling River Basin	Steenkoppies Aquifer	San Luis Potosí Basin	California State
General information					
Size of the case of study (km^2)	22,378	1,064,000	311	300	410,000
Aridity classification	Semiarid	From arid to humid, most of it falls under the arid or semiarid classification	Semiarid	In the limit between arid and semiarid (Precipitation: 400 mm PET: 2,000 mm)	From arid to humid, but most of the southern 2/3 are arid or semiarid
Water availability and/or scarcity	EI = 0.8 (High water stress)	EI = 0.5 in 1995	Not mentioned	Not mentioned	Nearly all of CA's principal sources of water supply are currently utilized at full capacity
Drought recurrence	High	High	High	High	High
Typical drought duration of severe droughts	3–5 years	Up to 10 years	1–2 years or more	Not mentioned (the chapter focuses on groundwater flow identification)	3–5–9 years

(continued)

Table 27.3 (continued)

Name of the case of study in Section 3	Spain	Australia	South Africa	Mexico	United States of America
	Jucar River Basin	Murray-Darling River Basin	Steenkoppies Aquifer	San Luis Potosí Basin	California State
Main natural sources of water	Surface water and groundwater	Surface water	Groundwater	Surface and groundwater	Surface and groundwater
Main water uses addressed in the chapter, which could be affected by the drought	Agriculture and urban supply	Agriculture and urban supply	Agriculture	Urban supply	Agriculture, urban supply, hydroelectricity
Main environmental issues addressed in the chapter	Low flows in rivers during drought water quality deterioration during drought impact of water abstractions on wetland during drought	Low flows in the river	Low flows at the spring during droughts	Water quality deterioration in aquifer	Ecosystems and endangered species. Delta ecosystems being affected by rise of sea level due to climate change
Main infrastructures of the water resource system(s) mentioned in the paper	Reservoirs, wells, canals, treatment plants, irrigation distribution systems	Reservoirs, irrigation distribution systems	Wells	Wells (even though, for the supply of San Luis Potosi, surface water from reservoirs is used as a main source	Reservoirs, canals, wells, artificial recharge facilities, treatment plants

(continued)

Table 27.3 (continued)

Name of the case of study in Section 3	Spain	Australia	South Africa	Mexico	United States of America
	Jucar River Basin	Murray-Darling River Basin	Steenkoppies Aquifer	San Luis Potosí Basin	California State
Administrative dimension of the case of study	River Basin	River Basin (although states play a relevant role)	Aquifer and catchment and recharge area	Aquifer and catchment and recharge area	State
Institutional settings in the study area	River Basin Organization since 1936 with stakeholders' participation since 1936. Water users associations are well consolidated, and present in the RBO	River Basin organization (MDBA) since 2005. Previously, River Basin Commission (MDBC) in which states were represented	Claims are sent to the Ministry of Water Affairs and Forestry (DWAF). But also lawsuits are common. Water users associations are being established.	Not mentioned	California Natural Resources Agency and California Department of Water Resources
Existence of water plans	Since 1980s	Not mentioned, but there are reports of the Murray-Darling basin sustainable yields project.	Not mentioned	Not mentioned	Not mentioned, but they exist
Existence of drought plans	Since 2007	Not mentioned	Not mentioned	Not mentioned	Not mentioned
Focus of the chapter	Drought planning and management in Spain and application to the 2005–2008 drought	Assessment of the impacts of climate change in the characteristics of future droughts	Management of water scarcity in an overexploited aquifer	Management of water scarcity in an overexploited aquifer	Impacts of climate change on future hydrology, water scarcity and environment

(continued)

Table 27.3 (continued)

Name of the case of study in Section 3	Spain	Australia	South Africa	Mexico	United States of America
	Jucar River Basin	Murray-Darling River Basin	Steenkoppies Aquifer	San Luis Potosí Basin	California State
State of research and technical development					
Level of knowledge on the physical behavior of the components of the WRS and interrelationship between them	Quite good knowledge level	Not mentioned	Authors suggest to improve the level of knowledge	Authors suggest to improve the level of knowledge	Quite good knowledge in most WRS
Existence of adequate model(s)	Ample portfolio of hydrological, water quality, hydro economic simulation and optimization models. Regularly used and updated	Many models developed, in the Murray-Darling Basin sustainable yields project	Very simple approach model, not a distributed flow model of the aquifer. Studies have been started in this direction	Very simple approach model, not a distributed flow model of the aquifer	Models for different WRS, and a hydro-economic model for a big portion of California
Existence of Decision Support Systems (DSS)	Integrated DSS are in use for W.R Planning and real time drought risk assessment, early warning system, and as common shared vision among stakeholders	Not mentioned	Not mentioned	Not mentioned	The hydro-economic model can be considered as a DSS for W.R planning, but not for drought risk assessment and management

(continued)

Table 27.3 (continued)

Name of the case of study in Section 3	Spain	Australia	South Africa	Mexico	United States of America
	Jucar River Basin	Murray-Darling River Basin	Steenkoppies Aquifer	San Luis Potosí Basin	California State
Implementation degrees of measures oriented to increase the available resources					
Increase surface reservoir capacity	Already developed	This type of solution is considered irrelevant by the authors	Does not apply in this CS	Not mentioned	Suggested in the chapter
Increase groundwater extraction capacity (either permanent or "drought wells")	Already developed	Not mentioned, since the scope of the chapter is on surface water	Does not apply, since it seems that the aquifer is overexploited	Does not apply, since it seems that the aquifer is overexploited	Suggested in the chapter
Increase the capacity of direct reuse of reclaimed wastewater	Partly developed. Under consideration	Not mentioned	Not mentioned	Not mentioned	Suggested in the chapter. Already developed in some basins
Increase the capacity of desalination of seawater or saline water	Remains as a future option, mainly for urban supply, but not considered so far	Already developed for the urban supply of Adelaide	Does not apply in this CS	Does not apply in this CS	Suggested in the chapter
Increase of capacity to import water from other WRS or basins	Not considered in this CS	Not considered in this CS	Does not apply in this CS	Not mentioned	Suggested in the chapter

(continued)

Table 27.3 (continued)

Name of the case of study in Section 3	Spain	Australia	South Africa	Mexico	United States of America
	Jucar River Basin	Murray-Darling River Basin	Steenkoppies Aquifer	San Luis Potosí Basin	California State
Implementation degrees of measures oriented to water conservation and efficient management of water resources					
Increase of the efficiency of water conveyance and distribution systems	Implemented in most systems, and under development in other	Proposed measure	Increase efficiencies in pipelines and irrigation equipment	Not mentioned	Implemented in most uses, and under development in other
Increase of the efficiency in water use in all sectors	Implemented in most uses, and under development in other	Proposed measure	Increase of scientific based irrigation scheduling	Not mentioned	Suggested in the chapter, mainly for urban demands
Design of better operating rules for WRS	Operating rules developed for this WRS	There are no explicit operating rules for the entire Murray-Darling WRS	Not mentioned	Not mentioned	Existing in some WRS
Conjunctive use of surface and ground water	Common practice	Not mentioned	Does not apply to this CS	Mentioned in the chapter, but not intentionally developed	Implemented in some WRS, potential expansion or application in other. Increase of this practice is suggested in the chapter
Indicators or curves to trigger different measures and to define their intensity (early warning systems for drought)	Developed and in use	Not mentioned	Not mentioned	Not mentioned	Not mentioned

(continued)

Table 27.3 (continued)

Name of the case of study in Section 3	Spain	Australia	South Africa	Mexico	United States of America
	Jucar River Basin	Murray-Darling River Basin	Steenkoppies Aquifer	San Luis Potosí Basin	California State
Water pricing	Water itself is not priced, but capital and O&M costs of infrastructure are paid by means of water tariffs	Not mentioned	Suggested measure to be considered	Not mentioned	Not mentioned
Water markets	Partly developed, mainly for environmental protection	Highly developed, and some suggestions for improvement are made	Suggested measure to be considered	Not mentioned	Partly developed
Water cost recovery	Close to full recovery	Not mentioned	Not mentioned	Not mentioned	Not mentioned
Metering of flows in water diversions from water sources and individual metering of water supply	Most diversions are metered. All households' supplies are measured. Many individual farmers' supplies are measured, but not all	Not mentioned	Limited number of flow meters, but provisions for future increase of monitoring	Not mentioned	Not mentioned
Use of remote sensing technologies in order to monitor water consumption by crops, or the existence of undeclared water uses	Developed in Mancha Oriental aquifer for 100,000 ha in order to control groundwater abstractions	Not mentioned	Not mentioned	Not mentioned	Not mentioned

(continued)

Table 27.3 (continued)

Name of the case of study in Section 3	Spain	Australia	South Africa	Mexico	United States of America
	Jucar River Basin	Murray-Darling River Basin	Steenkoppies Aquifer	San Luis Potosí Basin	California State
Definition of environmental flows in rivers for different seasons	Defined in the WRS Plans	Not defined	Suggested measure to be considered	Not defined	Suggested in the chapter
Flow augmentation in springs or wetlands inflows when they are affected by abstractions in aquifers or rivers	In practice	Suggested in the chapter for the lower basin	Mentioned as a possible future measure	Not mentioned	Suggested for the delta
Effective control of flows and quality of wastes in water bodies	Developed and in use	Not mentioned	Does not apply in this CS	Does not apply in this CS	Not mentioned in chapters, but developed and in use in several WRS
Monitoring of water quantity and quality in water bodies	Developed and in use. Automatic monitoring system gathers and sends data in real time to the basin authority	Not mentioned	Mentioned as a possible future measure	Not mentioned	Not mentioned
Monitoring of ecosystem health; provision of emergency measures in case of danger (e.g., excess of biomass in reservoirs with low storage)	Developed and in use, but could be improved	Not mentioned	Does not apply to this CS	Does not apply to this CS	Not mentioned

27.4.2 Concluding Comments

As a conclusion, we can say that, from a hydrological and WRS perspective, aridity, water scarcity and drought are different concepts, but all are present in the cases studied in Section 3, or at least, are the driving forces of their storylines. The scales are different, but the portfolio of available measures to provide information is quite similar. The goal, then, is to find the adequate combination of measures to help identify solutions to their problems that use the best knowledge and tools available for analysis, but ensure that this process is understood and has participation by stakeholders in order to ensure that the solutions are feasible not only from the technical perspective, but also from a social, economic, environmental, and other perspectives.

A central theme of these chapters is the challenges for future planning and management of drought that climate change and population increase will produce. A few chapters in this section focused on the impacts of climate change on future hydrology and WRS components (as water demand) and, hence, on future water availability (and hence on water scarcity) and on the characteristics of future droughts. In these cases, and even in the others which do not deal explicitly with the climate change subject, it seems quite clear that water scarcity and droughts will be exacerbated by climate change. But, as discussed in the cases of California and Mexico, population increases also will likely have strong effects on future water scarcity and drought impacts.

27.5 Summary of Economic Consideration of Drought

Growth in population and wealth is adding pressure to already stressed water resources and their dependent ecosystems thereby creating problems of water degradation in many basins around the world. Droughts are recurrent climate fluctuations but climate change is anticipated to modify their natural intensity and frequency and duration. The combined effects of human induced water scarcity and stronger drought spells would have severe impacts on human economic activities and the natural environment. Incentives and economics can influence how severe the impacts of drought are. This section highlights how policies influence the economic impacts of droughts in Australia, California, South Africa and Spain as discussed in chapters in Section 4.

27.5.1 Economic and Institutional Instruments in Water Management

Water markets have been introduced in Australia as a mechanism to address water scarcity and have played an important role during drought spells. The Australian Murray Darling basin is at present the most active water market in the world. The chapter on Australia describes the policy reforms and the administrative arrangements leading to water reallocation through water trading and the subsequent large economics gains due to this trading.

The success of water trading in Australia is based on several provisions that facilitate trading. One is the definition of a varying water allocation to each water right holder, depending on the water available for each specific season. Another is the separation of water property rights from land. A third provision is the capacity to monitor and enforce the defined water allocations of water right holders. The emergence of this water market and the ensuing flexibility in water reallocation has produced very large economic gains to society, especially during drought spells. Chapter 20 presents evidence on the significant benefits of water trading during the recent drought in the Murray-Darling, with estimated benefits of 1 billion USD during the drought year of 2007–2008.

A challenge to water markets is the third party impacts of water trading. These third party impacts can be ignored lowering the transactions costs or else taken into account, but then the transaction costs would reduce the benefits of water trading. Australia has chosen to mostly ignore third party impacts, and this has facilitated the operation of water markets. Another problem with water markets is that the stream flows decrease because water allocations that were previously unused are traded, thus expanding extractions, and also because the gains in irrigation efficiency at the parcel level reduces drainage and return flows to the environment. To avoid these problems, Connor and Kaczan suggest two different alternatives. One is reviewing the impact of trading on stream flows and then adjusting the allocation of tradable water to preserve environmental flows, knowing that trading based on diversions may erode environmental flows but it has lower transaction costs. The second alternative is to base trading on consumptive use, which has higher transaction costs that may hinder water trading.

The California chapter analyzes different water management alternatives by choosing a portfolio of water transfers, water storage and conservation, reuse and desalination. Significant reductions of water supply under droughts or climate change can be accommodated by such a flexible water system. A hydro-economic model is used to estimate the optimal economic response to water scarcity. The model is used to evaluate the response of agriculture to severe droughts, the adaptation strategies of the urban sector, and the impacts of water transfers among irrigators and between irrigators and urban sectors. The finding is that the optimal allocation, storage and conveyance of water in space and time significantly reduce the impacts of drought.

The results from the model indicate that water trading could substantially reduce the impacts of droughts, together with the conjunctive use of ground and surface waters. The costs of the recent drought to agriculture in the Central Valley of California are estimated at almost 1 billion USD from revenue losses and additional pumping costs, and involve losses of 21,000 jobs. Water scarcity costs from future droughts or climate change are simulated with the model, showing that flexible water allocation schemes could reduce scarcity costs from 1.59 to 0.12 billion USD. The results demonstrate the potential of these flexible water allocation schemes to reduce both the large scarcity costs of agriculture, and the very large scarcity costs of urban uses.

But this type of solution based on water trading is difficult to implement in California as shown by the failure of the water bank in the 2009 drought, which was blocked by the water exporting regions. The economic incentives of water trading and the current judicial processes are not sufficient to guarantee the attainment of this optimal solution, which requires stronger institutions involving stakeholders' cooperation.

In the case of South Africa, drought spells cause significant damages to the economy, with damages reaching 2.4 % of the gross domestic product during the 1991–1992 drought. South Africa has dealt with droughts by developing large inter-basin transfers and water storage facilities. During droughts, the traditional response has been restrictions to water supply and emergency government assistance to the livestock sector. South Africa is moving from emergency measures to confront drought spells, towards drought planning that emphasize the adoption of risk reduction strategies based of self-reliance by integrating risk in farm management and planning. But this requires major changes in the structure of economic incentives and also structural adjustments in the policy and institutional setting. The current efforts for drought management are focused on improving drought information, coordination and recovery assistance, but new initiatives are required for developing measures to promote self-reliance and sustainable water and land use practices. The chapter by Hassan highlights the potential economic instruments offer in inducing autonomous long-term adaptations to droughts as favored by the new generation of South African drought policy. He suggests that economic instruments would be particularly helpful if designed to encourage adoption of less water-intensive land and water-use methods through subsidies and credit facilitation, together with the promotion of drought-risk insurance for crops. A challenge with such approaches is the requirement for major changes in the structure of economic incentives, policy and institutional settings to improve drought information, coordination and recovery assistance, and measures to promote self-reliance and sustainable water and land use practices.

Water scarcity is becoming a problem in most Spanish basins, aggravated during drought spells. Water scarcity and quality degradation is the consequence of the enormous development of irrigation and the growing pollution loads from urban centers and industries. The more acute problems of water scarcity are located in the south and eastern basins, where highly profitable crops such as vegetables and fruits are cultivated under intensive production systems. Water scarcity implies that the potential impacts from droughts could be much more damaging in economic and environmental terms. The response of Spanish basin authorities to drought spells under these aggravating scarcity conditions has been a more sophisticated and complex elaboration of responses and adaptation measures.

The Ebro and the Jucar basins are presented as case studies of responses to water scarcity and droughts. The responses are not the same in these two basins given the different pressures on water resources and the enforcement capacity of water authorities over extractions. Important water policies such as the National Irrigation Plan or the National Hydrological Plan have been unable to reverse or dampen the progressive water scarcity in both basins. This gives the impression that the Spanish society and policy makers prioritize expansion of water supply over protection of water resources.

The size of irrigated agriculture in Spain is similar to California. In Spain, 8.5 million acres are irrigated with 20 million acre-ft to generate 18 billion USD in crop revenues, while in California 9.2 million acres are irrigated with 33 million acre-ft that yield 22 billion USD in crop revenues. These large irrigation extractions are pressuring water resources and creating significant environmental damages. The resulting threats to human water security have been compensated in both Spain and California with multibillion dollar investments in water technologies, in the form of water transfers, water storage and conservation, advanced irrigation systems, wastewater treatment plants, seawater desalination, and water reuse. Despite these similarities on the size of irrigated agriculture and of large investments in water technologies, the approach to water management in Spain is very different from California.

Water management in Spain relies on institutional instruments, including negotiated limits on extraction with compensation, and sharing of cuts to extraction amongst sectors. In California and Australia, management is mostly based on judicial processes and economic instruments. The Spanish legislation was modified to induce the development of water markets, but without much success. The main institutional organizations in Spain are the River Basin authorities, which manage water and deal with the problems of water scarcity and droughts. The distinctive feature of this institutional arrangement is the key role played by stakeholders in basin authorities, with stakeholders involved in all their governing and management bodies. Other distinct features in Spain are Basin drought plans based on monitoring and on a system of indicators, drought management rules specifying how reduced water will be shared for every watershed board within each basin, and urban contingency management plans.

27.5.2 Concluding Remarks

The Australia and California cases provide evidence that water trading as a mechanism to reallocate water from low to high profit uses can be a valuable drought management strategy. Both regions already have water markets in operation and evidence from their operation is that economic benefits can be considerable. The hydro-economic modeling from California also provides evidence that there is likely to be economic benefits from investments in infrastructure to allow conveying and storing water in ways that can reduce drought impacts and reduce dry period supply constraints. Results show that water reallocation and technology adoption are essential components that reduce the hydrologic and economic impacts of water scarcity.

In South Africa, Hassan outlines how economic instruments rather than command and control seem more desirable incentives for drought adaptation. In Spain, the short-run response to droughts is institutional, with basin authorities organizing the collective action of stakeholders in water scarcity and drought events. But the long-run response to water scarcity has been through water policy initiatives involving very large investments in water technologies in order to ensure water security.

The experiences in Australia, California, South Africa and Spain indicate that there are different approaches for the management of water scarcity and drought. One is water markets where water is managed as a private good, and the other is collective action where water is managed as a common pool resource. There can be private and social net benefits from water markets and collective action approaches, and welfare gains under both approaches are consistent with economic theory. Both approaches are intertwined. For example, well-functioning water markets require a great deal of cooperation by stakeholders within a strong institutional setting. The third party effects of water markets, including the environment impacts, call also for a robust institutional setting in order to reduce the transaction costs of water trading. Conversely, the institutional approaches in Spain and South Africa would work better by using carefully designed economic instruments. These incentives would introduce more flexibility in the institutional process of decision making and implementation. The water management experiences in the four countries indicate that both water markets and institutional approaches require substantial policy efforts focused on nurturing stakeholders' cooperation.

27.6 Summary of Water Management and Policy

Given the importance of water in almost every aspect of life, it is not surprising that different agencies, stakeholders, etc., all want to have some control over its use. One cannot help but appreciate the complicated nature of water management after reading these chapters, as there are many different layers of management and administration. Yet, one common theme that surfaces from the chapters on water management and policy in Mexico, Spain, and Australia is that planning and water use decisions all rest, first and foremost, within the auspices of a basin-level authority.[1] Most likely, and as elucidated by Meza-Gonzalez et al., the choice of making the central management unit the River Basin was to allow representation based on *hydrology* rather than existing *political boundaries*.

In Spain, River Basin authorities are in charge of hydrological planning, authorizations of surface water and groundwater extractions, water discharges, fines, flood and drought management, *inter alia*. In Mexico, the National Water Laws of 1992 and its subsequent amendments established basins as the primary water planning and management unit. In Australia, the Water Act of 2007 established the Murray-Darling Basin Authority (MDBA) as the lead unit charged with basin water sources management. The purpose of the MDBA, as Kendall notes (page 6) was to "… promote and co-ordinate effective planning and management for the equitable, efficient and sustainable use of the land, water and other environmental resources of the Murray-Darling Basin."

27.6.1 Drought Management

Drought has been a prime motivator for water reform as suggested by Dreverman. Similarly, Kendall notes that drought has played a major role in shaping water policy in Australia, from the influence of the 1895–1902 Federation Drought on the drafting of Australia's Constitution through to the influence of the 1996–2009 Millennium Drought on major reforms, including the 2004 National Water Initiative and the 2007 Commonwealth Water Act. After reading the Section V chapters, Dreverman's and Kendall's sentiments could be extended to any of the countries discussed in this book. For instance, Spain's National Hydrological Plan of 2001 contained a significant section on preparations for drought plans in response to what the government felt was a lack of preparation during the 1990–1995 drought. As Garcia-Vera and Galván-Plaza explain, Spain was in a fully advanced state of drought before it was officially recognized; consequently, only emergency measures were adopted. Emergency measures are an expensive response, especially compared to proactive mitigation.

Hence, the most recent droughts have resulted in some significant changes in how water is managed in semi-arid and arid environments. The following list of mitigation and coping mechanisms, while not meant to be exhaustive, highlights responses identified in Section V that have been considered or implemented to address drought.[2]

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[1] This is not to suggest that the basin authorizes in any of these instances can rule with impunity; rather, they are charged with management which does not necessarily translate into ownership. In the case of Australia, state governments ceded management but not ownership; similarly, as illustrated in both the chapters pertaining to Spain and Australia, under certain emergency conditions the federal government can appropriate temporary control.

[2] It should be noted that country-specific examples of these options will be provided but that the exclusion of a country in the examples does not mean that such an approach is not being used.

Increases in Storage. Water storage can aid in spreading out the temporal distribution of water within and across years. Most countries have used dams and reservoirs to combat drought and water scarcity in this manner. While the proliferation of dams has subsided in recent times (recall Fig. 1.1), using reservoirs and groundwater systems via conjunctive use continues to be popular as evidenced by the discussions in Section V. Garcia-Vera and Galván-Plaza, for instance, identify new storage capacity projects in Spain. Since 2000, several reservoirs were built in the Matarrana watershed to increase water use reliability, while two new reservoirs are being built in the Jalón basin. Within the Ebro Basin, the second largest investments identified within the new basin hydrological plans for the period 2010–2015 are water storage facilities.

Both Dreverman and Kendall highlight the critical role storage has played in addressing the temporal dimension associated with water scarcity and drought in Australia. Dreverman notes that water storage capacity in the Southern MDB provides reasonable capacity to cope with dry inflows in all but the most extreme conditions, while Kendall acknowledges that in response to the highly variable and low runoff in Australia, it stores up to seven years' worth of water supply to ensure consistently reliable water supply. With all this storage, a major concern in Australia, as Dreverman notes, is how to reduce the evaporative losses from storage. For example, the evaporative losses along the stretch of conveyance from Hume Dam down to Adelaide, South Australia (approximately 2,000 km) can be greater than 1,250 GL annually. Solutions are being considered, one response being to store water further downstream earlier in the season in those years where drought and meeting critical human water needs may be a concern.

California, meanwhile, has significant storage capacity but, as indicated in Rossi et al. more is likely required. This additional requirement is partly due to the change in precipitation and, subsequently, runoff in California's largest reservoir, the Sierra-Nevada Mountains. It is observed that the yearly distribution of runoff is occurring earlier in the year; California's man-made storage is not adequate to capture that volume over a shorter time period. As Rossi et al. note, though, the debate in California is not about whether more capacity will be needed, but rather the type of storage. The competing options include more dams and man-made reservoirs versus conjunctive use.

Water Transfers. Slightly related to water storage is the opportunity for water transfers. Water transfers are a mechanism to meet demand in one region where water is scarce by moving it from another region where water is less scarce. Each of the countries/regions discussed in Section V benefit from water transfers. In Spain, for instance, southern and eastern regions have higher consumptions rates than available supplies; hence, water transfers (e.g., from the Tagus Basin to the Segura Basin) have been used to reduce water scarcity in those regions.

One concern with water transfers, a concern raised in Dreverman and Maier et al. (Chap. 3), is how to reduce the often significant conveyance losses with transferring water. Echoing such concern, Meza-Gonzalez et al. suggests that in

Mexico nearly 44 % of the water is lost in the distribution process, a loss that has very real implications for the drinking water supply availability.[3] Given the relative scarcity of water in the northern parts of Mexico absent drought, evaporative and conveyance losses simply magnify an already bleak problem.

Transfers are certainly a significant issue in California, as water moves from the north of the state to the more populated south. As Rossi et al. explain, each day the main water district in southern California moves more than 1.6 billion gallons of water through its distribution system. The concern highlighted in Rossi et al. though, is how environmental issues in the north and the restrictions that can be imposed on transfers south due to these issues can impact the degree of water scarcity in the south. These restrictions seem to have provided additional motivation for the Southern California water districts—districts that historically have been very reliant on northern water—to more intensely explore opportunities for increase within-region supplies.

Wastewater Recycling. An advantage of using recycled water, as Rossi et al. note, is that it reduces reliance on imported water, adds to the water portfolio of an agency, and is locally reliable in times of drought. Agencies in Southern California are increasingly considering recycled wastewater as part of their water portfolio. Rossi et al. discusses efforts to recycle water from sewage treatment plants, particularly during critical times, and provides an example of the significant investments Southern California is making in this supply-side approach by highlighting the case of the Groundwater Replenishment system (GWR). The chapters on Mexico and Spain briefly mention recycling. Meza-Gonzalez et al. acknowledges the benefits from wastewater recycling in dealing with pollution. The main polluting industries in Mexico are sugar refineries and chemical, yet wastewater treatment of industrial sewage from a technological perspective has been limited which, in turn, limits the supply of recycled water. In the case of Spain, Garcia-Vera and Galván-Plaza call for future lines of research and development that generate more water supply sources, including wastewater reuse (which, as identified in Chap. 13, is already being used in the Jucar Basin).

Desalinization. Similar to recycled wastewater, desalinization is an option that can be used to increase the supply of water. For instance, Garcia-Vera and Galván-Plaza point out that water management in the Segura Basin includes desalinization, and that in 2005 the Spanish government approved the AGUA project, which entailed building desalinization plants along the Mediterranean coast. At present there are approximately 700 desalinization plants in Spain. With the significant advances in technology which drives down costs, Rossi et al. sees desalinization as an evolving alternative in California. Indeed, approval for a 50 million gallon per day desalinization plant in Southern California was recently granted and building has begun. The advantages of desalinization include improving water quality,

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[3] While this is an area where some efficiency gains can be made, the issue of return flows should be acknowledged to truly identify the system losses [see, e.g., Qureshi et al. (2010)]. To wit, conveyance losses (and even runoff from fields) often may reappear in the system for use elsewhere.

improving water supply reliability, reducing the necessity to import water from other regions, and to complement local and regional water recycling programs.

Groundwater Pumping. Groundwater has traditionally been, and continues to be, a significant source of water supply in semi-arid and arid environments. Groundwater resources provide many services, including providing flow into streams, lakes, and wetlands, serve as sources of irrigation water for growers, and are often primary drinking water sources. A common and well-known problem with groundwater resources is that they are often treated as a common property resource, lack monitoring, and thus are over-exploited. In Mexico, there is serious concern about the rate at which groundwater is being pumped. As Meza-Gonzalez et al. emphasize, this is partially due to the subsidies on electricity consumption and suggests that if the subsidies were eliminated, water extractions would decrease by 35 %. Meza-Gonzalez e al. suggest that better monitoring of groundwater sources and the elimination of permission by private agents to exploit and use public groundwater resources is required to restore these systems to a sustainable level.

Similarly, basin authorities in Spain are limiting the granting of groundwater concessions, and implementing more rigorous inspections to impede the overdraft of aquifers. At the same time, though, a numerous groundwater systems are being developed and improved in urban systems for use in emergencies. Within California, as Rossi et al. note, groundwater harvesting is often used as part of a water districts water portfolio. As noted earlier, groundwater serves as a valuable storage option and, perhaps, as a substitute to dams or reservoirs. Given the value of sustainable groundwater resources, Rossi et al. informs us that California is pouring significant funds into protecting these resources, with better monitoring being a necessary ingredient.

Exchange Centers and Water Trading. On the demand side, governments are increasingly looking towards markets to help ration scarce resources and this is no different with water. Spain, for instance, has instituted water exchange centers that allow basin authorities to publicly bid for the acquisition of water rights which are subsequently transferred within basin to users willing to pay. As Garcia-Vera and Galván-Plaza note, though, transactions have been limited. In Mexico, the National Water Laws in 1992 legally enabled the creation of water markets. Meza-Gonzalez et al. emphasize, though, that while such opportunities for trading does not yet occur, trading opportunities would be beneficial to agriculture as it would result in an increase in the productivity of water use as water moves toward more valuable commodities. The fact that 77 % of water in Mexico is allocated to an agricultural industry that contributes just 4 % to GDP suggests that water trades likely will occur with some water moving out of agriculture.

Australia has one of the most, if not the most, mature water markets globally. As Dreverman states, trade of allocation entitlements has reduced the level of water scarcity in Australia. Indeed, and citing Connor and Kaczan in Chap. 20, over that last few years nearly 1/3rd of all water in the MDB has been traded. Consequently, Dreverman states that water trading has likely reduced the economic impact of drought on the economy by 50 %.

Efficiency Improvements. Efficiency improvements, sometimes referred to as water conservation measures, are a popular strategy to deal with water scarcity and drought from a demand-side perspective. The largest investments in decreasing water scarcity in Spain as noted by Garcia-Vera and Galván-Plaza, for instance, are associated with the modernization of irrigation systems. In Mexico, given that a significant portion of agricultural land is still using somewhat inefficient irrigation systems (46.2 % of the land uses least-efficient systems), there are significant opportunities for irrigation efficiency improvements and water savings. The National Water Initiative, as Kendall points out, represents a shared view and commitment by the state and federal governments of Australia to increase water use efficiency. Rossi et al. meanwhile, cite the fact that the California Department of Water Resources is working with water agencies and the legislature to develop a plan titled, "20 by 2020 Water Conservation Plan," which is intended to permanently reduce per capita water use by 20 % by 2020. Activities promoted to encourage water conservation and efficiency improvements include both technological and behavioral improvements to indoor and outdoor water use for different sectors.

Two issues of concern regarding the use of efficiency and conservation measures are raised in Section V. First, and this is an issue raised in Rossi et al. adoption of conservation and efficiency projects, at least the highly capitalized ones, likely will require additional rate increases when the costs of running agencies are covered by water use-related revenues. As is clear in the latter part of Rossi et al., rate increases in the presence of efficiency improvements by households may result in public discontent and have political implications. The more development that occurs, though, the larger the base over which expenditures can spread; hence, the capitalized (fixed) costs per household will decrease with population increases and rates may not necessarily increase following reductions in per capita water use.

The second issue relates to an Australia experience in which it intended to retard the granting of concessions for an already over-allocated River Murray through caps on diversions. Following the implementation of the caps, conservation and efficiency measures reduced water application rates per hectare in many areas, which also reduced return flows back to the system. This effect, coupled with land use change, ended up having a detrimental effect on River Murray flows. Kendall outlines a number of possible solutions to this problem, including the creation of an environmental water holder that can purchase water when ecosystems and flows require such action, a minimum flow requirement through the system, or defining water use in terms of consumption, rather than diversion.

Water Pricing. Water pricing, as pointed out in Garcia-Vera and Galván-Plaza, is a core policy of the European Water Framework Directive, particularly to implement the cost-recovery principle of the Directive. While full cost recovery is rarely achieved, European nations, including Spain, are practicing at least partial cost recovery, often at local levels. Yet to date, at least in Spain, there are no plans to use water pricing as a tool to ration use. In Mexico, water is highly subsidized and rarely priced to recover costs; indeed, it is underpriced to such an extent that only 11 of its 31 states recover their costs. In California, rate increases have been significant to counter the decrease in water revenues from less water availability due to drought. Again, agencies have fixed costs commitments that do not vary with water use. Since most agencies revenues are tied to volume, as volume decreases so do revenues. In addition to rate increases to cover costs, subsidies to agricultural water users have been decreased.

Environmental Concerns. Environmental concerns have certainly played a significant role in water policy and management. Water for many years was allocated for "reasonable" or "beneficial" uses such as irrigation for agriculture, drinking water, industry, and power generation. More recently though, as evidenced by each of the chapters in Section V, reasonable and beneficial use of water includes maintaining ecosystems and environmental services. For instance, the Ministry of the Environment in Spain requires that all new irrigation projects must comply with conditions of an environmental impact assessment study. Meza-Gonzalez et al. highlight the fact that in Mexico, the National Water Plan specifically identifies environmental sustainability as one of three pillars that the basin water authority is to optimize over. It is clear from Rossi et al. that water for environmental purposes trumped the need for water by irrigators south of the San Francisco-Bay Delta and of water agencies in Southern California. In Australia, the National Water Initiative created an environmental water holder and a minimum flow requirement for the River Murray.

27.6.2 Concluding Remarks

An appropriate phrase that may summarize the main message from Sect. 27.6 is that "necessity is the mother of invention." It is clear that drought and severe water scarcity episodes have changed water policy and water management. Furthermore, drought management and water plans are being developed with concern over climate change and increased population pressures. The responses include a variety of supply and demand side measures. There does seem to be a movement towards finding more locally reliable supplies that likely include wastewater reuse and desalinization. Furthermore, uncontrolled pumping from groundwater systems is becoming less acceptable, while opportunities to increase water use efficiency are increasingly being explored. Finally, as water becomes scarcer, governments and water agencies are realizing the importance of better monitoring systems, and the potential benefits of having access to multiple water supply sources, including those that would become available via water markets.

27.7 Final Considerations

The multinational and interdisciplinary perspective offered in this book suggest that the consequences of more intense and frequent drought can be very costly and even irreversible in some instances (e.g., in the case of particular ecosystem functions as identified in Sect. 27.2). Rossi et al. in Chap. 25 identifies drought as being an impediment to economic development within urban environments, while Kendall's vivid description of the devastating impacts on agriculture is an ominous reminder of what may occur should we plan poorly. Dreverman spends considerable time emphasizing that previous drought management plans in Australia were not adequate to guarantee enough water supply to meet basic human needs to certain communities under extreme and extended drought conditions. In the case of Mexico, where 36 % of the population does not have reliable access to clean drinking water in non-drought periods, Meza-Gonzalez et al. emphasize that extended drought can further exacerbate poverty and destroy livelihoods. In addition to potential damaging impacts on economic development, agricultural production, and human health and welfare, the authors all mention possible environmental impacts.

Despite the challenges, and in considering the summaries above, there seems to be ample reason to be optimistic about how society might address drought in the future. One reason to be optimistic is that there seems to be, at least with the cohort of scientists, water managers, and policy makers involved in this book, agreement on the main drivers of drought. For instance, in Chap. 23, Garcia-Vera and Galván-Plaza suggest that water scarcity will increase from additional demand for consumptive uses, environmental flows and the threat of climate change, and that drought will become more frequent while precipitation becomes more variable. Similarly, Kendall in Chap. 26 states water resources in Australia will be influenced by climate variability. The reason it is important to highlight the agreement between policy makers, water managers, and the scientific community is that agreement between these groups is a necessary condition for the development of effective and successful drought management plans and policies.

Another reason to be optimistic about our ability to prepare for drought, although perhaps a bit cautiously, is that there seems to be ample opportunity to reduce the per capita water use and increase or extend water supply as evidenced in the sections on agronomy and economics. From more efficient on-farm strategies that serve to extend or increase supply, to water markets and water banking that allow water to be allocated more efficiently geographically and temporally, to reuse and desalinization, there exists an array of approaches to reduce the degree of water scarcity in each region and, hence, the potential impacts of drought. The "cautionary" note, though, is included since adequate preparation for drought is not free. Drought preparation will likely involve financial and environmental costs as well as behavioral adjustments. Yet the opportunity costs associated with these factors will likely pale in comparison to the costs associated wit less-informed policies.

Two final points of consensus from various chapter are worthy of reiterating. First, managing drought efficiently and effectively requires real-time information on the biophysical elements of drought and the institutional arrangement to make decisions in an expeditious manner if required. There were numerous instances discussed in the chapters above, particularly in Sects. 27.5 and 27.6, where policy makers and water managers seemed what might be best termed, caught off guard, finding themselves in the midst of a drought and unprepared. Perhaps the country amongst the five discussed in this book that best serves as setting the bar regarding real-time biophysical indicators of drought is Spain. As emphasized in Chap. 13, Spain has developed, as part of its Special Drought Awareness and Mitigation Plans (SDP), numerous drought indicators that can provide real time information flows on factors such as precipitation, river and channel flow, reservoir volume, and other important water quantity and quality parameters. Such information allows Spain's growers, water managers, and policy makers to be much more proactive about drought management and prepared relative to if such information were lacking. Conversely, poor monitoring handcuffs policy makers and water managers in any potential efforts to efficiently and equitable manage water resources, especially during drought. This leads us to conclude that the ability to develop and implement effective strategies to address drought requires up-to-date information on the drivers of drought, the potential impacts of drought, and the effectiveness of various management strategies to cope with and mitigate drought.

Of course, real-time information is most valuable when it is translated clearly and expeditiously to the appropriate level of management for decision making. One can imagine the formation of a special drought committee (SDC) that would report to the appropriate water resource system governing body (which is often the (river) basin organization as discussed in Sect. 27.4). Furthermore, and as depicted in the Jucar River Basin case study, the presence of this SDC—which has the capability to make decisions more tailored to real-time situations than, say, a river basin organization—can be very useful. Such a SDC would maintain continuous monitoring in order to control the efficacy of the decisions, to follow the evolution of the drought and its impacts on users, water quality, and the environment. Finally, the SDC should have the capability to authorize emergency works in order to improve control and efficiency of water use, connectivity, additional source development (e.g., drought wells, direct treated wastewater reuse), and hence, to increase the reliability of the water supply.

The second point worth highlighting is the importance of a participatory and transparent approach to developing and administering drought policies. For instance, developing opportunities for growers to work with agronomists and water engineers will not only help to identify practical ways to manage water more efficiently, especially in times of drought, but will likely increase the strategic policy and management measure adoption rates. Alternatively, requesting stakeholder input early on in the management and policy development process—a ubiquitous element in the more evolved water and drought management policies identified in Sect. 27.6—will likely reduce the number of policies that ultimately fail (or fail to gain approval) by identifying unfavorable and/or infeasible policies at the outset. Since allocation of water among consumptive users (and also to the environment) in situations of scarcity and drought is a source of conflict, it is crucial that an atmosphere of trust be developed among the stakeholders. As an example, consider the joint and participatory development of Decision Support Systems (DSS) for Integrated Water Resources Management that incorporated models at the WRS scale for the Jucar Basin (Spain) discussed in Chap. 13. This DSS, used to assess the effectiveness of a combination of potential strategies for the Jucar River Basin during drought, provided a common shared vision of the system, and transparency in the decision-making process. Stakeholders were able to assess, by using the DSS, the consequences of their proposed solutions, as well as the consequences of solutions proposed by other stakeholders, facilitating consensus in order to solve the conflicts.

Finally, on the subject of a multidisciplinary perspective and approach, the fact remains that water systems are linked to other natural and man-made systems with complex feedback effects. As such, drought impacts in a given catchment or basin may impact other catchments, basins, and ecosystems as well as human production, health, and well-being. A better understanding of the linkages across these different systems, with input from multiple disciplines, will provide us with a better understanding of the potential consequences from changes within any particular element within a system. The days of reliance on engineers alone to build our way out of water crises are gone. Collaborative effort with interdisciplinary input seems to be a more encompassing and informative approach for providing policy makers and water managers with the fullest understanding of the consequences and available strategies for addressing drought.

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