DROUGHT
ASSESSMENT

BY: R. NAGARAJAN

Springer

Drought Assessment

Drought Assessment

R. Nagarajan
Center of Studies in Resources Engineering
Indian Institute of Technology Bombay, India

Springer

A C.I.P. Catalogue record for this book is available from the Library of Congress.

ISBN 978-90-481-2499-2 (HB)
ISBN 978-90-481-2500-5 (e-book)

Copublished by Springer,
P.O. Box 17, 3300 AA Dordrecht, The Netherlands
with Capital Publishing Company, New Delhi, India.

Sold and distributed in North, Central and South America by Springer,
233 Spring Street, New York 10013, USA.

In all other countries, except India, sold and distributed by Springer,
Haberstrasse 7, D-69126 Heidelberg, Germany.

In India, sold and distributed by Capital Publishing Company,
7/28, Mahaveer Street, Ansari Road, Daryaganj, New Delhi, 110 002, India.

www.springer.com

Cover illustration: Photographs taken by the author at Nanded district, Maharashtra, India.

Printed on acid-free paper

Printed in India.

Preface

Climate is one among the triggering factors for drought and the geographical location of its occurrence coincides with earth's climatic classification. Experts provide varied definitions according to viewpoints based on selective parameters. Drought events that were reported from various parts of the world and their intensity are widespread. Forecasting of drought is general but it is looked from different perspectives by different experts. The first chapter of this book illustrates the abovesaid aspects. Understanding of the precipitation, cloud, weather, monsoon, tropical conditions, different type of weather forecasting, rainfall measurement and methods of analysis which offer greater insight of the drought initiation and preparedness activities, is given in Chapter 2 on Meteorology. Surface water from river, lake and ponds (natural or man-made) and ground water from hard and soft rock aquifer are the sources for supplementary irrigation when there is no rainfall. The quantum of water availability for supplementary irrigation from a source and its sustainability prior to decision making have been dealt in the third chapter. Crop growth and production depends on the suitability of crops for available soil type, seed quality, water and micro level humidity/temperature condition that favours the growth of pests. Chapter 4, Agriculture, discusses soil moisture holding capacity of the soil and crop water requirement for planning purposes.

Studies have shown that initiation of drought has certain relationship with the inducing parameters of a given test site. Threshold values of those parameters with reference to meteorology, hydrology, agriculture, socio-economics and environment and their classification were indicative of the forthcoming events. These indicators are being used for declaration processes across the globe. Analytical methods (statistical/mathematical) are extensively used in identifying the indicators. Some of the significant methods are discussed in the next chapter, Drought Indices. Remote sensing data offer information about the object without touching it with the help of electromagnetic spectrum. Sensors from air-borne and satellite-borne platform provide enormous information about the land cover features on a regular basis. Data collection platforms, and visual interpretation digital image enhancement techniques that are being used for assessment of drought indicative parameters are discussed in Chapter 6 on Satellite Remote Sensing. Integrated analysis of observational data needs to be brought into a common domain prior to analysis. Chapter 7 elaborates creation of spatial data base from the conventional to recent collection modes and their analysis aspects under title Spatial Data and Geographical Information System. Creation of information base from the historical events and adopted management techniques is an important aspect in the knowledge based decision making and scenario creation at sites.

Risk from the drought events are not only due to lack of resources, crop production, people, livestock and economy but also social network. Information on drought vulnerability on micro and macro levels is effectively used in management of resources. Vulnerability Assessment, Chapter 8, highlights the vulnerability and risk assessment of various sectors. Vulnerability of revenue villages under a given rainfall scenario offer preparedness exercise. An overview of the drought affected countries in tropical and non-tropical regions, their natural resources and on-going management practices, collated from other sources is presented as Resources, Drought Events and Management Profile of Countries as last chapter of the book. In order to meet the natural hazard events, the available resources need to be effectively utilized.

It was possible to provide desired information at one place only with the support from Indian Meteorological Department; Central Water Commission; Indian Council of Agriculture Research; Central Research Institute for Dry Land Agriculture, Hyderabad; Central Arid Zone Research Institute, Jodhpur; Census of India; National Bureau of Soil Survey and Land Use Planning, Nagpur; Geological Survey of India; Ground Water Survey Board; drought monitoring centres and Indian Space Research Organization located in India and International Water Management Institute; UNEP/GRID; UNOSAT; Bureau of Meteorology, National Land and Water Resources, Government of Australia; Bangladesh Agricultural Research Council; Environment Canada; Alberta Agriculture, Food and Rural Development, Canada; China Meteorology Agency (CMA); National Oceanic and Atmospheric Administration (NOAA); US Department of Agriculture (USDA); US Geological Survey (USGS); National Drought Mitigation Center and others whose help is acknowledged.

Encouragement and support extended by my colleagues at Indian Institute of Technology Bombay is acknowledged. Mr. Ajay More, Mr. Amit Kumar Jena, Mr. Agastheeswaran, Mr. Rajat Kumar Panda, Mrs. Sangita Mishra and Mr. Edwin Jebamani's (IIT Bombay) help in the GIS and remote sensing data analysis is acknowledged herewith. My interactions with Prof. M.S. Swaminathan, Chennai; Dr. Balaji, ICRISAT, Hyderabad; Dr. Ramakrishna, CRIDA, Hyderabad; Dr. K.D. Sharma, NIH, Roorkee; Dr. Prakash, DMC, Bangalore; Dr. R.S. Rao, CAZRI, Jodhpur and others from government departments, institutions and persons from the drought affected villages, have made me realize that observations from the sites along with the monitoring tools are the only effective ways in combating drought.

Trust this book would make a difference in the decision making in drought related activities.

June 2009
Mumbai, India

R. Nagarajan

Contents

1

Introduction

One third of the world's population lives in areas with water shortages and 1.1 billion people lack access to safe drinking water. Globally, drought (7.5%) is the second-most geographically extensive hazard after floods (11%) of the earth's land area. The percentage of area affected by serious drought has doubled from the 1970s to the early 2000. Europe and Asia, Canada, Western and Southern Africa, and Eastern Australia experienced widespread drought. Mega-droughts hit the Yucatán Peninsula and Petén Basin areas with particular ferocity, because of thin tropical soils, which decline in fertility and become unworkable when deprived of forest cover; regular seasonal drought, drying up surface water; the absence of ground water; the rarity of lakes, especially in the Yucatán Peninsula; the absence of river systems, such as in the Petén Basin; tropical vegetation which requires regular monsoon rain, and heavy dependence upon water-based intensive agricultural techniques, particularly in the Classic period. Rising global temperatures appear to be a major factor provoking more frequent and intense droughts in sub-tropical areas of Asia and Africa. It is reported that the Northern Hemisphere has recorded an increase of 1°C in the past 1000 years and the fluctuation is quite rapid during 1850 and 2000 and the upward trend still persists. The climate models predict a global warming of about 1.4°C-5.8°C between 1990 and 2100 and the sea level to rise by 9 to 88 cm. With increase in global temperatures the world is likely to experience more hot days and heat waves and fewer frost days and cold spells.

The pattern of earth's temperature as recorded from balloon and satellite measurements tend to exceed during the past few decades indicating the pattern of green house warming. Even a small rise in temperature is likely to be accompanied by many other changes in cloud cover and wind pattern. Even though periods of extreme dry/wetness and cold/hot conditions are a normal phenomenon within the dynamic climate condition, their severity and duration are expected to increase. The period of unusual dryness (i.e. drought) is a normal feature of climate and weather system in semi-arid and arid regions of the tropics of the world and it covers more than one-third of the land surface vulnerable to drought and desertification. Much of the earth surface has become desert since the dawn of the civilization and more areas are in the process of desertification. The existing 18, 16 and 6 million km^2 area of degraded lands in Africa, Asia and Australia respectively are on the increase due to rainfall variation and human activities. The variability in rainfall is significant in the tropical areas (Fig. 1.1). Mid-continental areas of US grain belt, vast sections of mid-latitude Asia, sub-Saharan Africa and parts of Australia are expected to experience drier and hotter conditions. The site-based variation exceeding 60%, with heat stress, shifting monsoons and drier soil, reduce yields by as much as one-third in the tropics and subtropics irrespective of crops with maximum heat tolerance.

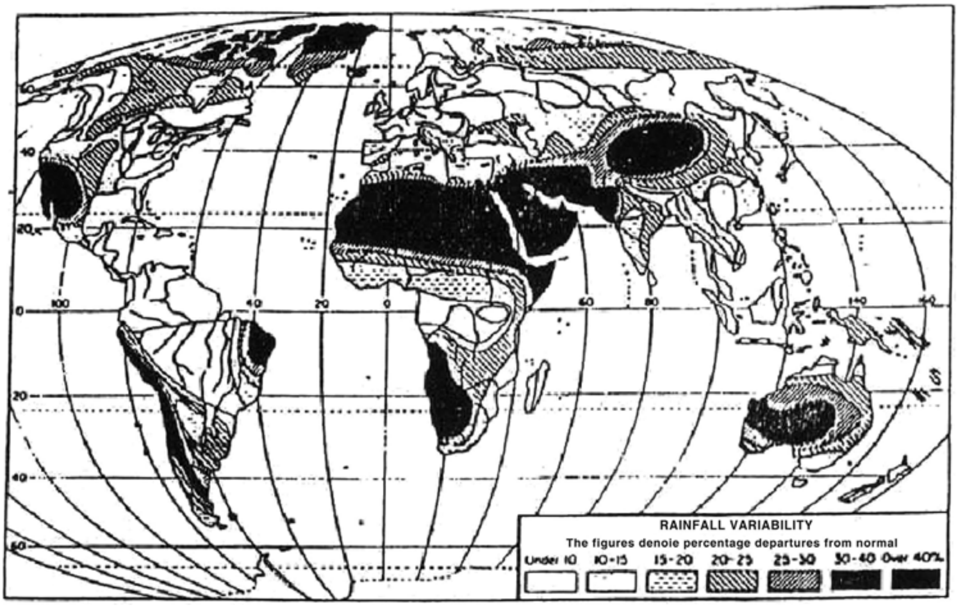


Fig. 1.1: Variability of rainfall on global area.
Courtesy: FAO

1.1 Climate Classification

Koppen's climate classification system (1918) is based on annual and monthly averages of temperature and precipitation. There are five climatic types: ***A*** – *Tropical moist climate* – all months are warm and no real winter season; ***B*** – *Dry climate* – deficient precipitation and potential evaporation and transpiration exceed precipitation; ***C*** – *Moist mid latitude* climates with mild winters – warm-to-hot summers with mild winters. The average coldest month is below 18°C and above –3°C; ***D*** – *Moist mid-latitude* climates with severe winters – warm summers and cold winters. Average temperature of warmest month exceeds 10°C and coldest monthly average below –3°C; and ***E*** – *Polar climates* – extremely cold winters and summers. Average warmest temperature is below 10°C and there is no summer season.

Thornthwaite's classification system has introduced the temperature and precipitation measurements related to natural vegetation and climate. It emphasizes the importance of precipitation and evaporation on plant growth. Dry climate is divided based on their degree of dryness – arid (BW) or Steppe/semi-arid (BS). Semi-arid regions are located on the margins of the arid regions receiving average rainfall that varies from 20 to 40 cm and also called as steppe. UNESCO's (1979) aridity classification is based on Penman's approach i.e. ratio of annual precipitation and mean annual potential evaporation wherein ratio < 0.03 is hyper-aridity; 0.03-0.20 for arid zone and 0.20-0.50 for semiarid zone; dry sub-humid 0.5 to 0.65; moist sub-humid 0.65 to 1.0 and humid >1.0. It varies with the purpose of the classification and may relate to features of earth's surface – geomorphology, pedology or natural vegetation which are the effects/resultant of climate. Semi-arid regions are those receiving moderate rainfall. Humidity and precipitation over the humid areas are very high.

1.2 Drought, Famine and Desertification

Drought is a period of drier-than-normal conditions that results in water-related problems. It is the period when rainfall is less than normal for several weeks, months or years, the flow of streams and rivers declines and water levels in lakes and reservoirs descent and the depth to water in wells increase. If dry weather persists and water-supply problem develops, the dry period can become a drought. The first evidence of drought usually is seen in rainfall records. Within a short period of time, the amount of moisture in soils can begin to decrease. Water levels in wells may or may not reflect a shortage of rainfall for a year or more after a drought begins (Fig. 1.2). Light to moderate shower will provide a cosmetic relief and soaking rain alleviate drought and provides some relief to drought areas. Water enters the soil to recharge ground water, which in turn sustains vegetation and feeds streams during periods when it is not raining. Multiple soaking rains break the drought. *Famine* results from a sequence of processes (natural or man induced) and events that reduces the food availability or food entitlements and causes widespread and substantially increased morbidity and mortality. It has occurred periodically in the history of ancient civilization in India, Egypt, Western Asia, China, Greece and Rome and also in other parts. Significant reported major famines in the world are shown in Table 1.1.

Table 1.1: Droughts/famines/food shortages during 1900-1998

Year	*Global*			*South Asia*		
	Events	*Killed*	*Affected*	*Events*	*Killed*	*Affected*
1998	34	3875	24942285	1	2541	-
1997	18	930	7236100	1	100	-
1996	8	-	8485590	2	32	-
1995	14	-	30230904	1	558	-
1994	9	-	15515000	1	161	-
1993	12	-	16331507	1	-	1175000
1992	29	2571	39444103	-	-	-
1991	20	2632	27418282	2	1023	250
1990	14	-	19253160	-	-	-
1989	10	5437	17632000	2	-	5806000
1988	22	-	12377500	2	450	200
1987	19	1427	317155767	5	510	302200010
1986	4	84	1499000	-	-	-
1985	18	100000	12016000	1	103	-
1984	35	458230	33546800	-	-	-
1983	55	520	162919729	3	-	121800000
1982	29	280	118057180	2	-	102000000
1981	20	-	5146180	1	-	-
1980	25	15	27418000	3	50	3500000
1979	13	18	205529000	8	687	200002000
1978	15	63	13574953	1	150	-
1977	21	-	9571400	1	-	250000
1976	10	-	-	-	-	-
1975	15	-	625000	1	14	-
1974	18	281500	1062000	1	-	-
1973	18	162500	110916665	3	-	101500000
1972	19	662500	102996665	3	-	100235000
1971	17	-	5930665	2	-	120000
1970	4	-	10225000	-	-	-
1969	14	200	2174204	1	-	48000
1968	9	-	3914217	-	-	-
1967	10	500600	1984427	2	500000	-
1966	9	508000	50360000	1	500000	50000000
1965	7	502000	51966000	2	500100	50000000
1964	9	50	2896000	5	-	1591000
1900-63	139	14581000	25282000	11	4651745	-

South East Asia			*West Asia*		
Events	*Killed*	*Affected*	*Events*	*Killed*	*Affected*
6	220	6020000	1	52	-
2	860	180000	-	-	-
1	-	2500000	-	-	-
1	-	2500000	1		808000
-	-	-	-	-	-
2	-	-	-	-	-
3	128	1139103	-	-	-
4	132	2754282	1	-	-
-	-	-	-	-	-
-	-	-	-	-	-
1	-	730000	-	-	-
5	-	-	-	-	-
1	84	1000	-	-	-
-	-	-	-	-	-
1	230	2000	-	-	-
1	-	200000	-	-	-
1	280	-	-	-	-
-	-	-	-	-	-
-	-	-	-	-	-
-	-	-	-	-	-
2	63	17953	-	-	-
1	-	3500000	2	-	-
-	-	-	2	-	-
-	-	-	1	-	-
-	-	-	-	-	-
1	-	3500000	-	-	-
1	-	-	-	-	-
-	-	-	2	-	2520000
-	-	-	1	-	-
-	-	-	-	-	-
-	-	-	-	-	-
-	-	-	-	-	-
1	8000	204000	-	-	-
-	-	-	-	-	-
-	-	-	-	-	-
-	-	-	-	-	-

(*Contd.*)

(*Contd.*)

Year	*East Asia*			*India*		
	Events	*Killed*	*Affected*	*Events*	*Killed*	*Affected*
1998	-	-	-	1	2541	1
1997	4	16	1860180	-	-	-
1996	-	-	-	1	-	-
1995	2	-	11060000	1	558	-
1994	3	104	6690000	1	161	-
1993	1	-	5800000	1	-	1175000
1992	1	-	12000000	-	-	-
1991	1	2000	5000000	1	500	-
1990	2	40	500000	-	-	-
1989	-	-	-	-	-	-
1988	2	2840	49000000	2	450	200
1987	-	-	-	3	510	300000000
1986	1	-	-	-	-	-
1985	1	-	-	1	103	-
1984	-	-	-	-	-	-
1983	2	-	-	1	-	100000000
1982	1	-	-	1	-	100000000
1981	2	-	-	-	-	-
1980	1	-	-	1	50	-
1979	2	-	-	5	599	200000000
1978	1	-	6000000	1	150	-
1977	2	-	-	-	-	-
1976	1	-	-	-	-	-
1975	-	-	-	-	-	-
1974	1	-	-	-	-	-
1973	-	-	-	1	-	100000000
1972	1	-	-	1	-	100000000
1971	1	-	-	1	-	-
1970	1	-	-	-	-	-
1969	1	-	-	-	-	-
1968	1	-	2800000	-	-	-
1967	2	-	1905944	1	500000	-
1966	1	-	-	1	500000	50000000
1965	1	-	-	2	500100	50000000
1964	1	-	-	2	-	666000
1900-63	7	3500000	20000000	5	2751051	-

South Africa			*North Africa*		
Events	*Killed*	*Affected*	*Events*	*Killed*	*Affected*
-	-	-	1	-	2600000
-	-	-	-	-	-
-	-	-	2	22	110000
4	-	839700	1	32	-
1	-	45000	-	-	-
2	-	150000	-	-	-
5	-	770000	1	-	550000
-	-	-	1	-	8600000
1	-	35000	1	-	600000
1	-	1320000	-	-	-
2	-	2640000	1	-	-
2	-	1871000	1	-	3450000
2	-	1498000	-	-	-
1	-	880000	-	-	-
3	-	1537300	3	150000	8400000
4	500	273180	5	-	1040000
3	-	273180	1	-	-
1	-	273180	2	-	-
1	-	-	1	-	-
-	-	-	-	-	-
-	-	-	-	-	-
-	-	-	1	-	31400
-	-	-	-	-	-
-	-	-	-	-	-
-	-	-	1	-	-
-	-	-	-	-	-
-	-	-	-	-	-
-	-	-	1	-	137000
-	-	-	-	-	-
1	-	87600	-	-	-
2	-	264000	-	-	-
-	-	-	-	-	-
-	-	-	1	-	-
1	-	60000	-	-	-
1	-	5000	-	-	-
-	-	-	-	-	-

Source: EM-DAT: The OFDA/CRED International Disaster Database, Universite Catholique de Louvain, Brussels, Belgium.

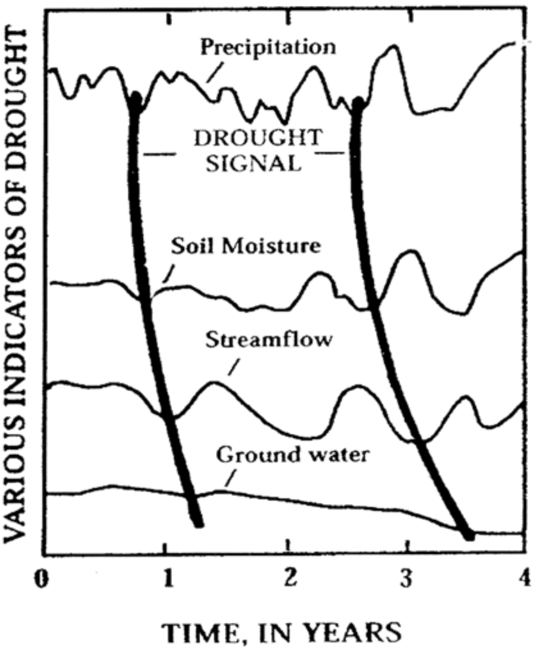


Fig. 1.2: Propagation of drought – rainfall to groundwater level.
(*Source:* Chagnon, 1987)

Desertification is the diminution or destruction of the biological potential of the land that can lead ultimately to desert-like conditions. It is an aspect of the widespread deterioration of ecosystem which diminishes or destroys the biological potential at a time when the increased productivity is needed. It is the means of conversion of a fertile or non-deserted land towards a dry infertile or deserted land (UNCOD, 1977). There is an acceleration of desertification in Africa-south of the Sudan-Sahelian region, in Andean South America and in parts of South Asia. There is a little change in China, but it is largely restricted in USA, China, India and USSR. *Land degradation* means reduction or loss, in arid, semi-arid and dry sub-humid areas, of the biological or economic productivity and complexity of rain-fed cropland, irrigated cropland, or range, pasture, forest and woodlands resulting from land uses or from a process or combination of processes, including processes arising from human activities and habitation patterns, such as (i) soil erosion caused by wind and/or water, (ii) deterioration of the physical, chemical and biological or economic properties of soil and (iii) long-term loss of natural vegetation (UNCCD). Drought, famine and desertification hazards were reported from some parts of the world at regular intervals. The observed temperature variation exceeds 50°C as in Thar deserts that spreads in Pakistan and India. The rainfall ranges between 25 and 200 mm/year in the desert areas which are expanding slowly.

Classification of Drought

A drought, unlike a flood, has no universal definition. To arrive at one, let us define four elements: *space* - river basin, region, country, hemisphere; *time* – month, season, year; *meteorological* – mean temperature and precipitation amount during a time period at a point in space; and *hydrologic* – runoff volume, mean groundwater level, and mean soil moisture during a time period at a point in space. There are several definitions in conveying the situation to the people involved by experts. Drought is defined as: "a period of dry weather"; "a condition when precipitation is insufficient to meet established human needs"; "comparison of normal precipitation months and years"; "a prolonged dry weather causing hydrologic imbalance"; "a time-space-duration distributions of percent of normal precipitation"; an index based upon hydrologic accounting (precipitation, evapo-transpiration, time and its relation to normal) 50 to 75% of normal summer rain; shortage of soil moisture in root zones of crops; potential shortage of water engendered by interaction between a climate event; and the adequacy of the safe yield of a system in relation to the demand level. The water deficit could happen even during flood, when the excess flow is non-usable in nature for consumption or utilization as a result of many complex factors acting and interacting within the environment. This interaction is such that drought often has no distinct start or end. Hence, there is a need for observable/ measurable indicators in realizing about the process.

Meteorological droughts are by definition region-specific, as the levels of precipitation and duration of dryness must be compared with the regional norms. Even within regions, considerable variations in atmospheric conditions result in deficiencies of precipitation**,** and there is a wide range of time scales over which a meteorological drought can occur. Meteorological drought is measured in terms of seasons, years, or decades of deficient precipitation. The duration of drought has a large impact on soil moisture and stream-flow, water supply in streams, shallow groundwater tables, and small lakes and reservoirs. *Hydrological drought* is generally defined on a watershed or river basin scale and measures the effects of periods of deficient precipitation on surface or subsurface water supply, such as stream flow, and on reservoir, lake and groundwater levels. Although all droughts originate with a deficiency of precipitation, hydrological drought refers to deficiencies in water supply caused by rainfall deficiencies over the watershed or river basin. Hydrological droughts generally lag behind meteorological and agricultural droughts, as it takes longer for precipitation deficiencies to show up in components of the hydrological system. When precipitation is below average for a long period of time, this is evidenced in declining surface and subsurface water levels, which may vary considerably, based on differing water uses.

Agricultural drought is complex in that its impacts depend on the magnitude, duration and timing of the drought, as well as on the responses of the region's soils, plants and animals to water stress. Insufficient topsoil moisture due to drought at planting may hinder germination, leading to low plant population per hectare (ha) and a reduction of final yield. A drought occurring in the later stage of crop development can destroy or deplete crop yields. Alternatively, the actual impact of drought on agricultural crops depends on the biological characteristics of the crops, stage of growth, and the physical and biological properties of the soil. *Socio-economic drought* occurs when water supply is insufficient to meet human and environmental needs, and emerges when a meteorological, hydrological, or agricultural drought adversely affects the supply and demand of economic goods.

Drought is grouped into: *Permanent* – characteristics of the driest climate, and drought vegetation are found and the agriculture is possible only by irrigation; *Seasonal* – planting dates and the crop duration should be synchronized with rainy season and residual moisture storage (arid and semi-arid regions); *Contingent* – irregular occurrence and there is no regular season of occurrence and *invisible* occurs even when there is frequent rainfall and occurs in humid region by Thornthwaite (1947). The chronically drought affected areas are identified by its meteorological data, revenue remission information, frequency of famine or scarcity and availability of irrigation. An *absolute drought* is a period of at least 15 consecutive days to none of which is credited 0.01 inches of rain or more. A *partial drought* is a period of at least 29 consecutive days, the mean daily rainfall of which does not exceed 0.01 inches and a dry spell is a period of at least 15 consecutive days to none of which is credited 0.04 inches or more. There is no definition that is either practical or adequate.

Short-term droughts are defined as periods with significantly below-normal-precipitation amounts for periods of months and are called meteorological droughts, because weather observations are used to define their start and end points and their severity. A variety of precipitation-deficit thresholds are defined based on the statistics of precipitation of a location from weather observations. Short-term droughts involve agriculture and domestic water use. A shortage of precipitation (meteorological drought) leads to a shortage of plant available soil moisture (agricultural drought). It also impacts natural environments, and, depending on the intensity of drought, is also responsible for increased wildfire hazards. The most pressing concerns for water managers are: (a) the short-term drought may mark the beginning of a long-term drought or the intensification of an existing long-term drought that may impact water supplies; or (b) the short-term drought may increase demand for water usage from systems that may not be designed for extensive lawn-irrigation and pool-maintenance requirements. In the latter case, short-term drought is more important as it relates to water system capacity as opposed to water resource capacity. *Long-term droughts* are defined as extended periods of below-normal precipitation lasting many months or even years.

It is often referred to as hydrologic droughts, since long dry periods with significant precipitation deficits lead to measurable reductions in lake, stream, and groundwater levels compared to seasonal normals. They are capable of directly impacting the water supplies of small community water systems and other cascading effects on energy production, manufacturing, etc. The long mega droughts are highly unusual but quite real possibilities. Maps and tables of the percent of normal precipitation expected during droughts at selected return periods and durations are useful. The return period or frequency analysis assigns a degree of likelihood to the precipitation deficit. A 100-year return period value is the amount of precipitation expected once in every 100 years on average. The actual time interval between two droughts of such magnitude will vary because what is really expressed in a 100-year return period is the amount of precipitation with a 1% chance of occurring in any given year. Frequency of droughts in the Aisa-Pacific region is listed in Table 1.2.

Table 1.2: Frequency of Drought (1950-80) in the Asia-Pacific Region

Country	*Drought Years*
Pakistan	1958, 1965, 1966, 1967, 1968, 1975, 1979
India	1950, 1951, 1952, 1958, 1963, 1965, 1966, 1968, 1972, 1974, 1979
Nepal	1964, 1974, 1977, 1979
Bangladesh	1950, 1957, 1959, 1965, 1972, 1974, 1979
Myanmar	1954, 1957, 1960, 1963, 1966, 1972, 1977
Sri Lanka	1961, 1966, 1967, 1975, 1976, 1977, 1979
Thailand	1952, 1953, 1954, 1955, 1958, 1966, 1967, 1968, 1972, 1974, 1976, 1977, 1978, 1979
Malaysia	1958, 1959, 1961, 1963, 1972, 1973, 1974, 1975, 1976, 1977, 1978
Indonesia	1961, 1962, 1963, 1964, 1966, 1967, 1968, 1972, 1973, 1976, 1977, 1979
Vietnam	1957, 1963, 1966, 1976, 1977, 1979, 1980
Cambodia	1954, 1955, 1958, 1963, 1968, 1960, 1972, 1974, 1976, 1977, 1979
Laos	1954, 1976, 1979, 1980
Philippines	1957, 1958, 1968, 1969, 1972, 1977, 1978

Source: Steyaert et al., 1981.

The said definitions are generic in their description of the phenomenon and define boundaries of the drought concept. But an operational definition identifies the precise characteristics and thresholds that define the onset, continuation and termination of drought episodes considering all the aspects (more than one index) required. Region-specific situation and status of drought is required in assessing the vulnerability. This will assist policy makers in taking the appropriate policy decisions. *Irrigation drought* reflects a disturbance in the normal irrigation practices due to a water scarcity in the water sources allocated to irrigation (Backeberg and Viljoen, 2003). This aspect helps in evaluating economic impacts for policy makers. *Agriculture drought types*: (1) Early season – delayed onset, prolonged dry spells after onset, (2) Mid-season – inadequate soil moisture between two rain events, and (3) Late season – early cessation of rains or insufficient rains. It links various characteristics of meteorological drought to agriculture impacts, precipitation shortage, differences between actual and potential evapotranspiration, soil water deficits, reduced ground water or reservoir levels etc. *Hydrological drought* is associated with shortfalls on surface or subsurface water availability (stream flow, reservoir and lake levels, ground water) on a watershed or river basin scale. Hydrologic droughts, therefore, are capable of directly impacting the water supplies of small community water systems. *Socio-economic drought* is defined as the supply and demand of water, forage, food grains and hydroelectric power.

Drought severity and recurrence are reported mostly from arid regions and partly some sections of semi-arid regions in India. Some of the *physical indicators* include rainfall, effective soil moisture, surface water availability, depth to groundwater, etc. *Biological/Agricultural indicators* comprise Vegetation cover and composition, Crop and fodder yield, Condition of domestic animals, Pest incidence, etc. and *Social indicators* are mostly impact indicators and include Food and feed availability, Land use conditions, Livelihood shifts, Migration of population, etc. However, the indicators that measure the rainfall that meets the requirements of water needs for crop production and drinking water (human and livestock) and availability of stored water in reservoir and ground water are only considered. As the perception of drought varies geographically across settlements, lack of proper assessment and warning systems lead to confusion or delay in reaching affected people/region, the indicators need to address the perception demands of the people at village, tehsil/mandal, district, state and country level. This should be based on data analysis and monitoring tools. In the absence of effective and informative indicators that are being followed, the Government spend significant amount in relief and rehabilitation. Maximum impact of drought is on the rain-fed medium and small farmers, followed by livestock raisers. Marginal farmers and weaker sections of the society get their relief offered by the governments and are addict to this relief which has eroded their traditional wisdom of drought understanding and conservation and management methods.

In drought-prone environments, the *risk features* are: High co-efficient of annual rainfall variation is found in areas that receive 350 mm to 800 mm. Significant rainfall variation is also observed over short distances. In the absence of irrigation or moisture conservation limits the crops grow from 60 to 180 days in a year. In association with low fertility and other soil characteristics, the paucity of moisture puts serious limits on the overall regenerative capacity of nature. *Farmer's strategy in managing risk* – Anticipation (historical experiences) of rainfall variability (ex-ante or risk management strategies) and response to drought (ex-post or crisis response) initiatives prior to climatic events. *Social adjustments* – Elaborate community-based, two-tier traditional irrigation institutions in the tank-based irrigation systems, one at enforcing and the other at the executive level for equal distribution of water. Collective decision to switch over to planting less water-consuming crops is required. The people living in drought-prone areas have learned to live with the hardships of drought. The observed positive and negative aspects in farmer's coping strategy against drought-induced problems are: *Positive aspects* include adoption of improved crop varieties; growing crops in non-traditional seasons; tapping of surface and ground water sources to provide life-saving irrigation of crops; and employment of non-farming activities in managing the shortfall of income and *Negative aspects* are increased population and pressure on land and other resources; increased high-yield crop instability (sensitive to rainfall variation) during drought; traditional strategies losing its efficacy; change from diversified crop system to mono-crop cultivation; abrupt reduction in income causing serious distress to farmers; and weakening of socio-economic institutions.

1.3 Factors Responsible

The factors attributed to drought initiation are: (1) ocean-atmosphere system, sea surface temperature anomalies, high temperature of the soil during drought and the increase in fine particles in the air, the high albedo in dry areas, (2) solar-weather relationship, and (3) monsoon mechanism and impairment of this mechanism (Rodier and Beran, 1979). Sahelain droughts are caused by (1) southward shift of Saharan trough leading to weak pressure gradient and a weak Inter Tropical Convergence (ITC), (2) progressive degradation of vegetation and increase in albedo, and (3) extra-tropical factors such as Westerlies etc. Precursors to the subsidence have to be understood in terms of atmospheric general circulation, which in turn are conditioned by abnormalities at the land and sea surface. There are many possible large-scale features of the general circulation, which are responsible for a given drought varying according to geographical circumstances. In tropical regions, such as India where rain is due to convergence, the migration or weakening of the inter-tropical convergence zone brings drought. These departures are in turn explained by anomalous behaviour in large-scale features of the circulation such as the St Helena (Sahel and Brazilian Nodest) or the Mascarene (India) highs. In higher latitudes, an upper level high-pressure system can block low-pressure systems. The 1976 drought in Europe has been ascribed to such a blocking high. Drought in India is correlated to irregular monsoon rainfall in space and time. It is attributed to weakening of

Mascarene cell in the Southern Hemisphere so that ITCZ is weakened to penetrate the Indian peninsula. The pressure at South Georgia Island (54°S and 36°W) correlates well with drought in India. In addition to high albedo, the local reduction of thermal gradient that sustains the early jet contributes to drought events. The various factors that are responsible for the drought events are shown in Fig. 1.3.

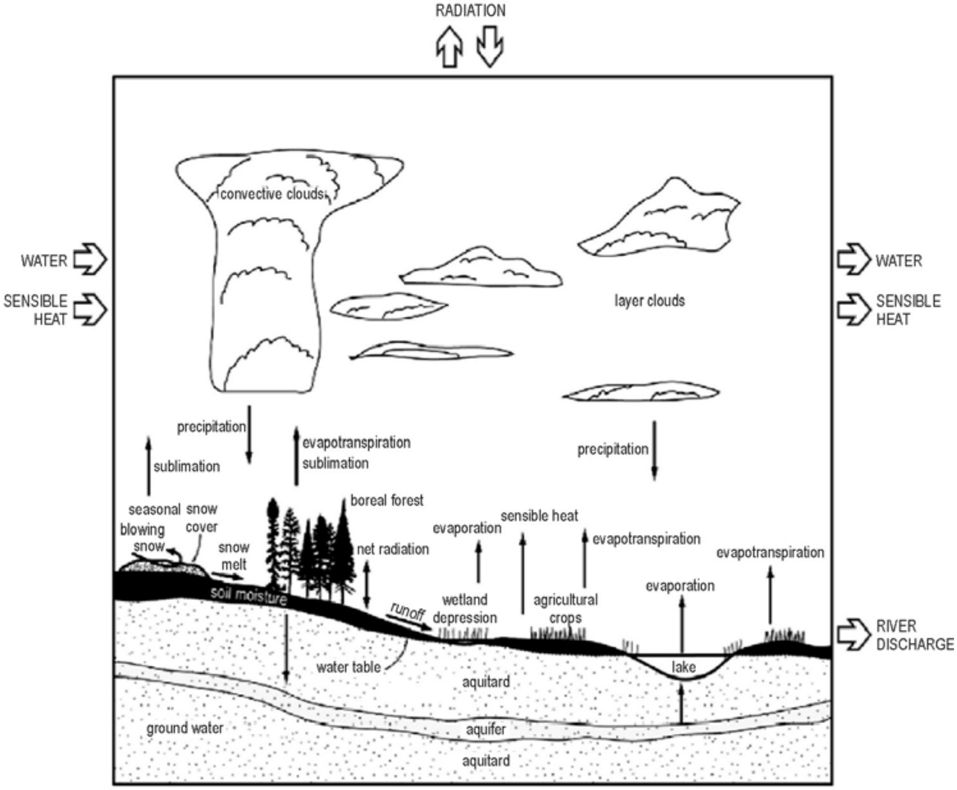


Fig. 1.3: Factors responsible for the drought events.

Precipitation

A decreased frequency of precipitation is the climatological factor that causes drought. The strongest drought signals are recognized during the season when the substantial precipitation expected failed to fall. The severe droughts in Great Plains (1890, 1910, 1930 and 1950) were associated with a lack of precipitation during the spring and summer, which normally are the wettest seasons (Borchert, 1971). The difference between normal precipitation and deficient precipitation commonly depends on precipitation from few storms. The 1930-60 records of Upper Colorado River basin show that about 50% of the annual precipitation results from only 25% of the storms. Therefore the lack of few large storms during a season can be sufficient to cause drought (Karl and Young, 1987). A period of below-normal rainfall does not necessarily result in drought conditions. Some rain returns to the air as water vapour when its evaporates from ground. Plant roots draw some of the moisture from soil and return it to the air through a process called transpiration. A single thunderstorm will provide some benefits as the shower, but it also causes loss of life and property if it is severe. Soaking rains are the best medicine to alleviate drought. It will provide lasting relief from drought conditions, but such multiple rains over several months may be required to break a drought and return conditions to do within the normal range. The amount of precipitation varies from year to year but over a period of years, the average amount is fairly constant in most of the regions. Normally, the average precipitation in desert is less than three inches per year and coastal areas receive more than 150 inches of average yearly rainfall. Even if total amount of rainfall for a year is about average, the rainfall shortages can occur during a period when moisture is critically needed for plant growth. Plants can die when there is no rain or only a very small amount of rainfall.

Temperature

Multi-year droughts are generally associated with higher than normal surface-air temperatures. 1986 drought in southeastern US had associated with surface-air temperature so much higher than normal that year with warmest July in 20th century (Karl and Young, 1987). 1962-65 drought in North East of USA is a major drought that was associated with lower than normal surface-air temperatures in all seasons. Measurements by Kunkel (1989) during the 1988 drought show that the enhancement of the Bowen ratio following drying out of the soil was itself capable of causing a rise in air temperature of 2°C. The precipitation below the average and the increase in temperature is as high as 0.5°C. The temperature difference is higher than the global variation. The deficit precipitation is observed to be continuous phenomenon from 1970 to 1994. However, there appears to be a slight improvement during 1998-99.

Wind Velocity and Evapo-transpiration

The most significant component of the hydrologic budget is evapo-transpiration. It varies regionally and seasonally. It varies according to weather and wind condition. It continues to deplete the limited remaining water supplies in lakes and streams and soil. About 67%, 29%, 2% and 2% is transmitted back through evapo-transpiration, surfacewater outflow, groundwater outflow and consumptive use of the rainfall respectively (USGS, 1990). It is not affected by solar radiation, surface area of open bodies of water, wind speed, density and type of vegetative cover, availability of soil moisture, root depth, reflective land-surface characteristics and season of the year. The maximum mean annual wind velocities average more than 14 miles/hour in central US and eight miles/hour in west coast and in mountainous parts of central US. Coniferous forest and alfalfa fields reflect only 25% of solar energy, thus retaining substantial thermal energy to promote transpiration; in contrast deserts reflect as much as 50% of the solar energy depending on the density of vegetation. The estimated mean annual evapo-transpiration ranges from maximum of 45 inches per year in Puerto Rico to minimum of 7.6 inches in Alaska. Daily fluctuations in evapo-transpiration also occur. On clear days, the rate of transpiration increases rapidly in the morning and reaches a maximum usually in early afternoon or mid-afternoon. The contour levels show the amount of evaporation/evapo-transpiration in mm. The midday warmth can cause closure of plant stomata that results in a decrease in transpiration.

Atmospheric Circulation

There has always been a deep curiosity about whether drought is repetitive or not. Solar variation has been indexed using sunspot numbers and magnetic polarity. Labitzke and Van Loon (1989) had discovered very high levels of correlation between solar flux and upper atmosphere response, which in turn is linked to surface phenomena. Ananthakrishnan et al. (1984) investigated the rainfall-sunspot links of India data sets and found that years of deficit can occur at any point in the sunspot cycle. Simple correlation and probability analyses indicated that some weak non-random features might be present. The El Nino phenomenon has been implicated in recent years in many adverse occurrences of flood and drought in South American continent. ENSO or El Nino refers to warm events in central and eastern equatorial Pacific. It is well publicized as an oceanic phenomenon and is also experienced during one part of the independently observed southern oscillation. El Nino events are found to occur when the sea surface temperature in the eastern equatorial Pacific was more than 1°C above average and the change from the previous year exceeded 2.5°C. The southern oscillation is indexed by the normalized pressure difference between Tahiti and Darwin. When the annual hydrograph of the Amazon with El Nino events are superimposed, two notable drought periods 1925/26 and 1982/83 do coincide with El Nino events, but other important droughts do not coincide (1941 and 1957). Farmer and Wigely (1985) found that 22 out of 25 years of drought events coincide with reduced rainfall due to El Nino.

Drought is associated with persistent or persistently recurring atmospheric circulation patterns. Drought in southeast US is generally associated with frequent recurrence of high-pressure (anticyclone) circulation. Daily circulation patterns associated with a drought (such as anti-cyclonic circulation of the preceding example) are not notably different from daily circulation patterns that occur during non-drought periods. Three-dimensional depictions of the atmospheric circulation patterns at a single instant (synopsis maps at several constant pressure levels) do not have features that are unique to droughts. Winter drought of 1975-76 in California is due to descending air beneath an abnormally strong winter-season ridge in the western US. The large upper level anticyclone that occurred during summers of 1952-54 produced widespread downward movement of air that inhibited precipitation throughout much of US.

Hemispheric Nature

A climatic perspective on drought is global or at least hemispheric; perspective that includes interactions between the atmosphere and its ocean and land boundaries. The causes of a drought cannot be restricted to the atmosphere above the area affected by a drought only. Day-to-day changes in precipitation, temperature, wind and so forth are defined as weather and not climate. Weather is not predictable even in principle for periods longer than about two weeks (Thiele and Schiffer, 1985). As a consequence of this limit on predictability the cause of drought when discovered will not define the actual sequence of dry and wet days during drought. Anomalies in surface boundary conditions commonly have been cited as being principal factor in causing and maintaining a drought. Although this approach avoids the question of what caused the boundary anomaly. It provides an important clue to understand the global aspects of drought producing processes. Voice and Hunt (1984) used a global general circulation model to study the dynamics of droughts as a response to specified tropical SST anomalies. The extensive SST anomalies for Australia illustrates that some of the mechanism are important in describing atmospheric and ocean relations. The experiment shows that SST anomaly has changed the evaporation rate. Then it began to perturb the atmospheric circulation because of their effect on precipitation i.e. because of latent heating of the atmosphere. The significant perturbations of the atmospheric circulation occurred over distant parts of the globe and produced areas of both increased and decreased precipitation. The beginning of a drought is difficult to determine but the end of a drought can occur as gradually as it began—9-10 years or more.

1.4 Effects of Drought

Drought historically has caused direct and indirect economic, social and environmental problems throughout the world. Even though some of them are unavoidable and others can be tackled. Drought induced economic losses include those resulting from impaired dairy and meat, crop, timber and fishery productions; lack of power; decline in agriculture-dependent industries; increased unemployment in agriculture and other related industries; strain on financial institutions and increased cost for transport of water and development of new sources. Studies on drought need to take into consideration the entire spectrum of human settlement. *Socio-cultural* (migration, occupational diversification, shifting settlements, disintegration of joint households, social losses, changes in social values, non-functioning of the socio-cultural institutions, disturbance in inter-caste relations), *Socio-economic problems* (loss of crop and livestock, production, pests, diseases and poor crop growth, livestock mortality, set back of occupational castes economy, distress sale of land and livestock, personal assets, increased indebtedness, scarcity of water, grass, fodder) and *Bio-physical problems* (removal of vegetation, overgrazing, wind erosion, predominant barren lands, shifting dunes, silting of village water ponds, over-exploitation of ground water) are encountered during drought. The requirement of the weaker segments constituting majority of the population was not fulfilled.

An evaluation of alternatives and the empirical study of decision-making and policy options are needed. Perception of the drought hazard varied according to (1) degree of aridity, (2) amount of drought experience, (3) personality differences, (4) age of the respondent, (5) educational level and (6) type of occupation. Perception of the drought effect/risk varied according to the type of occupation followed. The farmers (65%) of pastoral tract predominantly engaged in livestock rearing dependent on rainfall are generally less perceptive of the risk. These livestock breeders perceive the risk somewhat less serious than whose main emphasis is on agriculture only. Cultivators in rain fed and irrigated areas perceive the drought risks faster as their main occupation of cultivation is chiefly dependent upon rainfall. They perceive more seriousness of the consequences of drought

Social

During the drought period, irrespective of caste stratification in India, people work in common endeavour to save themselves on one hand and to create productive assets for the community on the other. It has brought together the landless farmers, the small marginal and bigger farmers despite their stratification level. It has also brought flexibility in the food habits of the people who made use of jowar, corn, milo, barley, gram, and tumba switch over to mateera seeds during acute droughts (Bharara, 1982). Social losses had occurred due to weakening of family solidarity, increasing conflicts, tensions and frequent distress coupled with the fear of dacoits, theft and social insecurity of the people in isolated settlements. Resource use depletion pertaining to scarce water, grass and fodder had increased tensions and conflicts among the agro-pastor lists. The wind erosion has completely blocked the approaching roads, but dwelling houses of Meghwals (groups in Rajasthan) had also been buried by sand deposition. 20% of the village's agriculture lands in Rajasthan had also been spoiled by wind erosion. Silting of village water ponds, by sand took place and 20-25 badas (fodder storage enclosures) of Meghwal, Jat and Rajput were blown away by wind during the last severe drought years.

Environment

Land use is affected by drought. If there is no rainfall at the time of sowing, land may not be sown at all and current fallow land may increase; crop intensity (gross sown area divided by net sown area) declines; and whatever area is sown may not be harvested because the production is so meagre that it cannot be used as fodder. Local vegetation and shrubs like *khejri* (fuel wood), *bhanwarli* (tanning industry), *kumbhat* (curd churner), and phog (coal conversion) were cut and sold by non-agro-pastoral community during drought periods. There is only a slight decline in crop intensity from 1.05 in a good year to 1.07 in drought from small farmers of pastoral and rain-fed tracts. These farmers prefer to work in scarcity relief centres (*attitude change*) (remunerative) rather than agriculture. The *primary effect of drought on soil* is the increased sheet erosion due to loss of plant roots and wind. The erosion of farm soil causes long-term loss in farm production even after the drought is over. Wildfires or man-made removal of vegetation enhances the potential for sheet erosion and soil removal. Soil is baked from these fires making them impermeable. Low level of *water* in rivers and lakes increases turbidity and salinity affecting fish habitat. Groundwater levels drop and spring flow decreases. Deeper aquifers may not be affected immediately. Wetlands may become dry until moisture returns. The decreased pressure on the primary and secondary water systems could create potential cross-connection and potential illness. Soil moisture can decrease, killing even the deeper plant root systems. Reservoir draws down and low stream flow affects recreation. *Air* becomes dry, warm and dusty, further desiccating the soil and increasing evaporation bodies of water. Respiratory ailments increase. Winds enhance sheet erosion from dried soils. Dust storms decrease visibility. Lack of precipitation and humidity increases concentration of dust and pollutants in air. *Eco-systems* depending on soil moisture or the presence of open water becomes damaged. Wetland and riparian animal and plant life are displaced or die. Dangerous animals may migrate to human settlement areas and become man eaters. Stressed vegetation and wildlife are more vulnerable to disease.

Agriculture

Significant effects felt by all the rain-fed crops are vulnerable to adverse effect as the entire area sown was damaged during drought years. During moderate drought year bajra (40.34%), moth (38.36%), sesamum (34.49%), moong (30%) and jowar (8.62%) were damaged in Rajasthan. Maize, rice, groundnut, pulses and sesamum production is decreased by 17, 16, 15, 11 and 8% during kharif; wheat, barley, gram and oil seeds decreased by 28, 15, 24 and 30% in rabbi crop during drought years. The mean annual production per ha of these had decreased significantly viz. Jawar, sesamum, bajra; small millet, cotton, maize and gram had decreased by about 78, 56, 64, 51, 30, 13 and 6% respectively. Drought leads to increase in area under culturable fallow and degenerated lands. Increase in fallow lands reduced net area sown from 58.71% to 47.53%. *Livestock* raising-cum-agriculture and agriculture-cum-livestock rearing were the most adversely affected having the highest extent of livestock mortality. Mortality of cattle, buffaloes, sheep and goats were 50, 24, 41 and 17% respectively.

1.5 Drought Forecasting

The scientific knowledge and historical data provide a basis for developing descriptive models of droughts. Under the assumption that the climate is stationary from year to year, the prior distribution provides a drought forecast for every year in an infinite series and to some extent it is identical for every year. A skillful forecasting is the aggregation of the prior distribution with present observations of various hydro-meteorological variables collected by the monitoring system. Application of likelihood function, on the observations, conveys any predictive information they contain about the immediate future. The skill of the forecast is demonstrated when the posterior distribution for a given period differs from the prior distribution. The forecast lead time is the instant up to which the hydro-meteorologic variables for preparing the forecast have been observed. The forecast period coincides with the time period over which the anticipated condition is defined. The lead time of the forecast is the time interval lapsed from the forecast time to the end of the forecast period (Fig. 1.4). For example, a forecast prepared on 1 January of

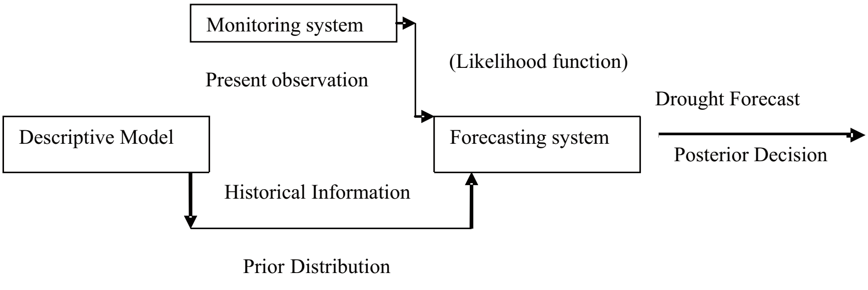


Fig. 1.4: Integration of descriptive model, monitoring system and forecasting system.

the runoff volume from 1 April through 30 September has a lead time of nine months.

Forecast performance and comparison: For a fixed lead time, the performance of a forecast may be gauged on an interval scale bounded by the performance of a naive forecast (specifying the prior distribution of the state) and the performance of a perfect forecast (specifying the actual value of the state). Performance measures characterize two attributes of forecasts: statistical quality and economic value. Popular measures of statistical quality are skill scores; they are independent of the use of forecasts. On the other hand, the economic value depends upon the decision problem in which forecasts are employed and is a function of both the lead time and statistical quality of forecasts. Two kinds of limits of the forecasts are to be kept in mind: The *theoretical limit* of predictability is imposed by the status of the hydro-meteorological sciences. To extend this limit, new knowledge about drought-causing processes must be gained and present theories must be expanded. The *operational limit* of predictability, naturally shorter than the theoretical one, stems from the level of technology and resources employed by a forecast service. Too sparse measurements of the atmosphere, too slow computers, or too little manpower are just a few examples of the limiting factors. Matching the operational and theoretical limits of predictability may seem an ideal goal (Krzysztofowicz, 1991). In order to interface with decision making on drought, it is necessary to examine the ultimate purpose of drought forecasts which is to provide information for decision making. It is essential that our normative needs of decision processes should be identified. A few exemplary questions: How should forecast uncertainty be expressed in order to provide a basis for rational decisions? What should be the lead time of forecasts for strategic planning and operational decisions? What is the optimal frequency of updating forecasts for adaptive (sequential) decision strategies? Naturally, the answers to these and other questions will vary across decision problems as they are the most sensitive – economically and otherwise.

Traditional Knowledge

Indigenous knowledge is acquired by observation of specific natural and social phenomena connected with the experience of supernatural power that influence life. Meteorological phenomena about the natural calamities (physical and social) are well understood by villagers to aid in drought predictions. They were developed out of the previous generation's experiences and observations. Belief in relationships between rainfall and natural elements like wind, wind direction, cloud and month, zodiac period (nakshtra), date (tithi) day and month, nakshatra (celestial stars) wind-heat and wind clame omen, moon-stars and their movements, etc. comprise climatic indicators of drought prediction. They may be classified into two categories (Mishra et al., 2002): (1) Observational Methods – Atmospheric changes; bio-indicators; chemical changes; physical changes; cloud forms and other sky features. (2) Theoretical Methods or Astrological Factors or Planetary Factors – Computation of planetary positions and conjunctions of planets and stars, etc.; study of solar ingress and particular dates of months; study of Nakshatra Chakras; study of Nadi Chakras, study of Dashatapa Siddhanta. Stars are known as Nakshatras; Constellation of stars: Rohini – Taurus; Mirigshirsha – Gemini; Ardra – Alpha orionies (astronomical name). (Ref: http://www.findyourfate.com).

Raman (1960) identified general atmospheric situations in India, as indicators of a healthy conception of the "ethereal embryo" of rain as: Gentle and agreeable wind from the north, northeast and east; Clear sky; Soft, white deep halo around the moon or the sun; Dark coloured sky – as dark as crow's egg; Sky overcast with huge, bright dense clouds; Needle shaped or sword shaped clouds; Blood red clouds; Rainbow in the morning or in the evening; Low rumblings of thunder; Lightning; Appearance of a "mock sun"; and Planets and stars shining in full form and with soft light. The following are the local beliefs regarding drought based on meteorological observations: (1) If the sky acquires a faint yellow colour, then there is less hope of rain; (2) If crow coloured clouds are observed throughout the day and night sky remains clear, drought is indicated; (3) If the velocity of wind is not high during Mrigshirsha constellation and high heat is not experienced during Rohini constellation a drought can be expected to follow; (4) If it does not rain Ardra (star) and no winds occur in Mrigshirsha, then drought would occur; (5) If the winds blow from east during the month of Shravan and from South-west during Bhadrapad, a severe drought could be expected; (6) Occurrence of wind with velocity on fifth day of the first fortnight of shravan month is indicative of severe drought; and (7) Occurrence of rain in the presence of sunshine is an indicator of poor rainfall in the near future.

Trees such as khejri (*Prosopis cineraria*), neem (*Azadirachta indica*), bordi (*zizyphus nummularia*); shrubs – aakra (*Calotropis procere*), kair (*Capparis decidus*), phog (*Calligonum polygonoides*), kheemo (*Leptadenia pyrotechnica*) and grasses sewan (*Lasiurus sindicus*) and mussa (*Tephorosia purpurea*) are the major species whose vegetation behaviour is taken to predict droughts. Pisharoty (1993) reported that the tree Amaltas or golden shower tree (*cassia fistuala*) is an unique indicator of rain. It bears bunches of golden yellow flowers in abundance about 45 days before the onset of monsoon. Kanani et al. (1999) observed that some of the behaviour of birds and animals are correlated to rains: (1) sparrow bathing in dust (good rain); (2) Chameleon climbs the tree and assumes black-white-red colour (immediate rain); (3) frogs start singing in initial days of Jyestha (May); (4) peacocks cry frequently (rain in a day or two); (5) Titodi or Lapwing bird lay eggs in the night on river beds (heavy rain); (6) camels keep facing northeast direction, goat does not browse and crow scratches in nets (immediate rain) and (7) Bapaiya bird sing early in the morning and snake climbs on the tree. When the jackal howls during the day, a great famine is certain. The she-camel knows beforehand and runs to and fro. She stamps her feet and does not sit when rain is to come. When sparrow bathes in the dust the rain will come, when it bathes in water, the rain will go. The validity of the local indicators was compared with actual nature of drought calculated on the basis of rainfall and crop maturity. About 61% and 39% respondents said that the predictions have come true in 55% and untrue in 45% cases.

Paleo-climatology is the study of the past climate that existed prior to humans began collecting instrumental measurements of weather. It uses natural environmental records to infer the past conditions. Records of rainfall or other indicators that reflect drought such as changes in lake salinity (changes in lake-dwelling species), vegetation or evidence of blowing sand are preserved in tree-rings (300 years), buried in the sediments of sand dunes and lakes. The tree-rings in a tree that is sensitive to drought provide a record of drought each year of the tree's growth. They provide information beyond the 100-year record provided by instruments. A more long-term look at the past droughts indicates that 20th century droughts do not represent the possible range of drought variability. Archaeological investigation has identified evidence of irrigation in Mesopotamia and Egypt as far back as the 6th millennium BCE, when barley was grown in areas where the natural rainfall was insufficient to support such a crop. In the Zana Valley of the Andes Mountains in Peru, archaeologists found remains of three irrigation canals radiocarbon dated from the 4th millennium BCE, the 3rd millennium BCE and the 9th century CE. These canals are the earliest record of irrigation in the New World. Traces of a canal possibly dating from the 5th millennium BCE were found under the 4th millennium canal. Sophisticated irrigation and storage systems were developed by the Indus Valley civilization in Pakistan and North India, including the reservoirs at Girnar in 3000 BCE and an early canal irrigation system from circa 2600 BCE. Large scale agriculture was practiced and an extensive network of canals was used for the purpose of irrigation. There is evidence of the ancient Egyptian pharaoh Amenemhet III in the twelfth dynasty (about 1800 BCE) using the natural lake of the Faiyum Oasis as a reservoir to store surpluses of water for use during the dry seasons, as the lake swelled annually caused by the flooding of the Nile.

The Qanats, developed in ancient Persia in about 800 BCE, are among the oldest known irrigation methods still in use today. They are now found in Asia, the middleeast and north Africa. The system comprises a network of vertical wells and gently sloping tunnels driven into the sides of cliffs and steep hills to tap ground water. The Noria, a water wheel with clay pots around the rim powered by the flow of the stream (or by animals where the water source was still) was first brought into use at about this time by Roman settlers in North Africa. By 150 BCE the pots were fitted with valves to allow smoother filling as they were forced into the water. The irrigation works of ancient Sri Lanka, the earliest dating from about 300 BCE, in the reign of King Pandukabhaya and under continuous development for the next thousand years, were one of the most complex irrigation systems of the ancient world. In addition to underground canals, the Sinhalese were the first to build completely artificial reservoirs to store water. The system was extensively restored and further extended during the reign of King Parakrama Bahu (1153-1186 CE). The oldest known hydraulic engineers of China were Sunshu Ao (6th century BCE) of the Spring and Autumn Period and Ximen Bao (5th century BCE) of the Warring States period, both of whom worked on large irrigation projects. In the Szechwan region belonging to the State of Qin of ancient China, the Dujiangyan Irrigation System was built in 256 BCE to irrigate an enormous area of farmland that today still supplies water. By the 1st century CE, during the Han Dynasty, the Chinese also used chain pumps that lifted water from lower elevation to higher elevation. These were powered by manual foot pedal, hydraulic waterwheels, or rotating mechanical wheels pulled by oxen. The water was used for public works of providing water for urban residential quarters and palace gardens, but mostly for irrigation of farmland canals and channels in the fields. In fifteenth century Korea, the world's first water gauge – *woo ryang gyae* (Korean), was discovered in 1441 CE by Jang Young Sil, a Korean engineer of the Choson Dynasty, under the active direction of the King Se Jong. It was installed in irrigation tanks as part of a nationwide system to measure and collect rainfall for agricultural applications. With this instrument, planners and farmers could make better use of the information gathered in the survey.

By the middle of the 20th century, the advent of diesel and electric motors led for the first time to systems that could pump ground water out of major aquifers faster than it was recharged. This can lead to permanent loss of aquifer capacity, decreased water quality, ground subsidence, and other problems. The future of food production in such areas as the North China Plain, the Punjab, and the Great Plains of the US is threatened. At the global scale 2,788,000 km^2 (689 million acres) of agricultural land was equipped with irrigation infrastructure around the year 2000. About 68% of the area equipped for irrigation is located in Asia, 17% in America, 9% in Europe, 5% in Africa and 1% in Oceania. The largest contiguous areas of high irrigation density are found in North India and Pakistan along the rivers Ganges and Indus, in the Hai He, Huang He and Yangtze basins in China, along the Nile River in Egypt and Sudan, in the Mississippi-Missouri river basin and in parts of California. Smaller irrigation areas are spread across almost all populated parts of the world.

Recurring or long-term drought can bring about desertification. Recurring droughts in the Horn of Africa have created grave ecological catastrophes, prompting massive food shortages, still recurring. To the north-west of the Horn, the Darfur conflict in neighbouring Sudan, also affecting Chad, was fuelled by decades of drought. Combination of drought, desertification and overpopulation are among the causes of the Darfur conflict, because the Arab Baggara nomads searching for water have to take their livestock further south, to land mainly occupied by non-Arab farming peoples. Approximately 2.4 billion people live in the drainage basin of the Himalayan rivers. India, China, Pakistan, Bangladesh, Nepal and Myanmar could experience floods followed by droughts in coming decades. The west coast of North America, which gets much of its water from glaciers in mountain ranges such as the Rocky Mountains and Sierra Nevada, also would be affected. As a drought persists, the conditions surrounding it gradually worsen and its impact on the local population gradually increases. Kazakhstan was recently awarded a large amount of money by the World Bank to restore water that had been diverted to other nations from the Aral Sea under Soviet rule. Similar circumstances also placed their largest lake, Balkhash, at risk of completely drying out.

Drought prediction and monitoring require information from: water management and agricultural applications; assessment of the current understanding of drought predictability and status of drought prediction efforts; identification of key model uncertainties that need to be reduced in order to accelerate progress on drought simulation and prediction; developing a prioritized list of observations that are critical for drought monitoring and model initialization, validation and development; and developing a plan for model experimentation in coordination with the drought monitoring and applications communities. As the weather plays an important role in the on-set and cessation of drought, information of cloud types and rainfall and temperature is discussed in the next chapter.

References

Ananthakrishnan, R. and Parthasarathy, B. (1984). Indian rainfall in relation to the sunspot cycle (1871-1978). *J. Climatology*, **4**, pp. 149-169.

Bharara, L.P. (1999). Man in the desert. Scientific Publishers, Jodhpur.

Borchert, J.R. (1971). The dust bowls in the 1970s. *Annals of the Assn. of American Geographers*, **61(1)**, pp. 1-22.

Chagnon, S.A. (1987). Detecting drought conditions in Illinois. Illinois State Water Survey Circular, pp. 164-187.

Farmer, G. and Wigley, T.M.L. (1985). Climatic trends for tropical Africa. Climatic Research Unit, Norwich, UK, 136 pp.

Kanani, P.R. and Pastakia, A. (1999). Everything is Written in the Sky!: Participatory Meteorological Assessment and Prediction Based on Traditional Beliefs and Indicators in Saurashtra. *Journal of Asian and International Bioethics*, **9**, pp. 170-176.

Karl, T.R. and Young, P.J. (1987). The 1986 southeast drought in historical perspective. *Bulletin of the American Meteorological Society*, **68(7)**, pp. 773-778.

Kunkel, K.E. (1989). A surface energy budget view of the 1988 mid-western United States drought. *Boundary-Layer Meteorology*, **48**, pp. 217-225.

Krzysztofowicz, R. (1991). Drought forecasting: Methodological topics from a systems perspective. *Stochastic Hydrology and Hydraulics*, **5**, pp. 267-279.

Lebitzke, K. and Van Loon (1989). Association between the 11-year solar cycle, the QBO and the atmosphere. Part III: Aspects of the association. *Journal of Climate*, **2**, pp. 554-565.

Mishra, S.K., Dubey, V.K. and Pandey, R.C. (2002). Rain Forecasting in Indian Almanacs (Panchangs): A case for making Krishi-Panchang. *Asian Agri-History*, **6(1)**, pp. 29-42.

Pisharoty, P.R. (1993). Plant that predicts monsoon. *Honey Bee*, **4(4)**, p. 12.

Raman, B.V. (1960). Prakash Marg, Parts I-II, Motilal Banarasidas Publishers Pvt. Ltd., New Delhi.

Rodier, J.A. and Beran, M.A. (1979). Some information on the UNESCO-WM report on the hydrological aspects of drought. Proceedings International Symposium on Hydrological aspects of drought, 3-7 December 1979, New Delhi, pp. 461-485.

Thiele, O. and Schiffer, R.A. (1985). Understanding climate – A strategy for climate. Modeling and Predictability Research, NASA Reference Publication, 1158, pp. 31.

Thornthwaite, C.W. (1947). An approach towards a rational classification of climate. *Geographical Review*, **38(1)**, pp. 55-94.

UNCOD (1977). Desertification – Luni development block, India, Nairobi, Kenya, pp. 1-5.

US Geological Survey (1990). National water summary 1987 – Hydrologic events and water supply and use: USGS Water Supply Paper 2350, 553 p.

Voice, M.E. and Hunt, B.G. (1984). The study of dynamics of drought initiation using a global general circulation model. *J. Geophysical Research*, **89(D)**, pp. 9504-9520.

Further Reading

Aswathnarayana, G. (1986). Drought in India. Proceedings National seminar on Drought, Desertification and Famine, New Delhi.

Chandini, R. (2000). India's experience in the use of traditional water harvesting in combating drought.

Golakia, B.A. (1992). Proverbs for predicting the moods of monsoon. *Honey Bee*, **3(1)**, p. 12.

IPCC (1998). Impacts of Climate change – An assessment of vulnerability risk. Watson, R.T., Zinyowara, M.C. and Moss, R.H. (eds.), Cambridge Press, pp. 571.

Le Comete, D. (1995). Weather highlights around the world. *Weatherwise*, **48**, pp. 20-22.

Min Seung-Ki, Kwon Won-Tae, Park, E.-Hyung and Choi Youngeun (2003). Spatial and temporal comparisons of droughts over Korea with East Asia. *International Journal of Climatology*, **23(2)**, pp. 223-233.

Obassi, G.O.P. (1994). WMO's role in the international decade for natural disaster reduction. *Bulletin American Meteorological Society*, **75**, pp. 1655-1661.

Palmer, W.C. (1964). Meteorological drought, Research paper 45, US Weather Bureau, Washington DC, February, pp. 58.

Palutikof, J.P., Farmer, G. and Wigley, T.M.L. (1982). Strategies for the amelioration of agricultural drought in Africa. Proceedings of the technical conference on Climate Africa, WMO, Geneva, pp. 228-248.

Sinha, B.P.C. (1989). Ground water in drought – Review of Indian Scene. Proceedings Inter-Regional symposium on Groundwater resources management in drought prone areas. 27 November-1 December 1989, New Delhi, pp. 165-189.

Swaminathan, M.S. (1975). India's Agricultural balance sheet. *The Ecologist*, **5(8)**, pp. 272-281.

USGS (1990). National water summary 1987 – Hydrologic events and water supply and use. USGS Water supply paper 2350. pp. 250.

Varshneya, M.C., Sheikh, A.M., Pandey, V. and Patel, H.R. (2006). Monsoon research: Almanac prepared for Gujarat. Anand Agricultural University, Anand, Gujarat, India, pp. 55.

Waple, A.M. and Lawrimore, J.H. (2003). State of the climate in 2002. *Bulletin of the American Meteorological Society*, **84(6)**, S1-S68.

WMO (1975). Drought. Special environmental report no. 5, WMO. no 403, Geneva, Switzerland.

WMO (1985). Climate variation, drought and desertification. WMO no. 653, Geneva, Switzerland.

2

Meteorology

The climate system as a whole is an extremely complex mix of different subsystems all interacting with each other on a wide range of time and space scales, e.g. the atmosphere, oceans, ice masses and the biosphere. The potential for variability from year to year and decade to decade, therefore, is very high. Given this high level of 'internal' variability, the significance or even the reality of possible external influences from sunspots, phases of the moon and so on, remains highly questionable on time scales shorter than millennia. The multi-disciplinary approach of the problem requires appreciation level knowledge of the rainfall processes that involve many of the countries disseminate rainfall, temperature and forecast information of the day in print (newspapers), visual (television) and audio (radio) media, internet (web site) and SMS (Short Message Services through mobile telephone). The people whose activities are related to weather such as farmers, agriculturists, farm extension workers and others anxiously wait for information with a view to prepare themselves on a regular basis. The cloud information is taken from the satellite images (coarse ground resolution), temperature and rainfall (installation points) and their forecast is based along with other weather-related parameters. Hence, there is a need to understand the cloud and their rainfall probability in deciding whether to irrigate now or wait for a day and the necessary resources to be arranged at field level. It is expected that people including meteorologists could appreciate the processes and the drought indices that they are using. This section outlines about the monsoon system, clouds, cloud pattern observation from satellites and rainfall measurement, so that non-agro-meteorologist could understand the rainfall processes and take a knowledge-based decision.

2.1 Weather

Surface wind circulation – climate belts: Atmospheric motion is driven by the uneven horizontal distribution of net incoming radiation and this uneven distribution is due to its latitudinal dependence. Oceans respond to this imbalance by attempting to move heat from the tropics and subtropics. The most outstanding feature about this distribution is its zonally banded structure; that is, it has the pattern of east-west elongated features aligned along latitude circles. The characteristic wind belts are: *Trade wind belts* – In the tropics, on both sides of the equator, lies a wide region where winds blow from east to west (easterlies) with a slight equator side tilt. This region is named as trade wind belt, because of the steadiness of the air flow. *Inter-tropical Convergence Zone* (ITCZ) – The trade winds from the northern and southern hemispheres converge into a narrow belt close to the equator and referred to as ITCZ. The convergence of the trade winds results in rising motion of the colliding air masses (to obey the law of mass continuity). This region is also known as the *doldrums*, where the weather is generally cloudy and periods of light winds are frequently interrupted by squalls and hard rains, making for a troubled and uncertain sea voyage. *Mid-latitude westerlies* – North and south of the trade wind belt (in the northern and southern hemispheres, respectively) lie regions where winds tend to blow from west to east (westerlies), and are therefore referred to as the westerly wind belts. Here the winds are highly variable and unsteady, especially during winters. This fact is not seen in our charts, clearly demonstrating that it is not enough to look at the mean. In these regions, during winter-time, mid-latitude storms and their frontal systems travel from west to east bringing frequent changes in weather. *Subtropics* – Between the trade wind regions lie in the subtropics, regions of divergence and subsidence, where sunny weather with little clouds and no rain prevails. These latitudes were referred to as the horse latitudes because winding up in these latitudes meant serious delays in the voyage. *Polar easterlies* – Poleward from the westerly wind belt, winds with a generally easterly component prevail. The air here is cold, dry and stable, especially during winter, and is accompanied by subsidence from above. *Polar front* – The convergence zone between polar easterlies and mid-latitude westerlies is referred to as the polar front. It separates the cold (and dry) polar air, and the relatively warm (and more humid) mid-latitude air. The polar front can be thought of as the average expression of the transient frontal systems that move along with mid-latitude cyclones.

The seasons in the tropics are dominated by the movement of the tropical rain belt, which oscillates from the northern to the southern tropics over the course of the year, thus causing the dry season and the wet season in turn. Temperate or tepid latitudes of the globe lie between the tropics and the polar circles. The changes in these regions between spring, summer, autumn and winter are generally mild, rather than extreme hot or cold and have very unpredictable weather. Within these borders there are many climate types, which are generally grouped into two categories: maritime (stable temperature because of oceans) and continental (warmer summers and colder winters).

Heat loss and reception are aided by extensive land mass. Subtropical climatic region is adjacent to the tropics, usually between 20° and 35° latitude in both hemispheres but occasionally found at slightly higher latitudes. A subtropical region should have at least eight months with a mean temperature of 10°C or above. Rainfall patterns vary widely throughout the subtropics including hot deserts, savannas, monsoon forests, humid forests and the warmer parts of the Mediterranean climate zone. The Torrid Zone includes most of Africa, southern India, southern Asia, Indonesia, New Guinea, northern Australia, southern Mexico, Central America and northern South America. In the Temperate Zones, the sun is never directly overhead, and the climate is mild, generally ranging from warm to cool. The four annual seasons – spring, summer, autumn and winter – occur in these areas. The North Temperate Zone includes Great Britain, Europe, northern Asia, North America and northern Mexico. The South Temperate Zone includes southern Australia, New Zealand, southern South America and South Africa. The Frigid Zones, or polar regions, experience the midnight sun and the polar night for part of the year – the edge of the zone experiences one day at the solstice when the sun doesn't rise or set for 24 hours, while in the centre of the zone (the pole), the day is literally one year long, with six months of daylight and six months of night. They are the coldest parts of the earth, and are covered with ice and snow. The North Frigid Zone (the Arctic) includes northern Canada and Alaska, Greenland, northern Scandinavia, northern Russia, and the Arctic ice. The South Frigid Zone (the Antarctic) is filled by the continent of Antarctica; the next closest mainland is the southern tip of Chile and Argentina, followed by New Zealand.

Climate is usually defined by what is expected or "normal", which climatologists traditionally interpret as the 30-year mean by understanding the concept of variability. **Weather** is the condition of the atmosphere over a brief period of time (one day or week). Climate represents the composite of day-to-day weather over a longer period of time. It is a set of all phenomena in a given atmosphere at a given time and includes interactions with the hydrosphere. It refers to the activity of these phenomena over short periods (hours or days) and the term climate, which refers to the average atmospheric conditions over longer periods of time. *Weather* most often results from temperature differences from one place to another. On large scales, temperature differences occur because areas closer to the equator receive more energy per unit area from the Sun than do regions closer to the poles. On local scales, temperature differences can occur because different surfaces (such as oceans, forests, ice sheets, or man-made objects) have differing physical characteristics such as reflectivity, roughness, or moisture content. Wind, cloud, rain, snow, fog and dust storms are some of the common weather phenomenon that we observe on the earth and occur in the troposphere (the lower part of the atmosphere) and do extend into stratosphere. Small changes on one part of the system can grow and create large impacts leading to large effects on the entire system. It is one among many factors for not being able to predict accurately the weather more than few days in advance. Weather of the land surface is influenced by sun and ocean as the sun heats up ocean waters for a period of time, water can evaporate. Once evaporated into the air, the moisture can spread throughout nearby land, thus making it cooler. Important weather belts on the northern and southern hemispheres and locations of frequently reported hurricane, typhoon and cyclone spots (in asterisk) are shown in Fig. 2.1.

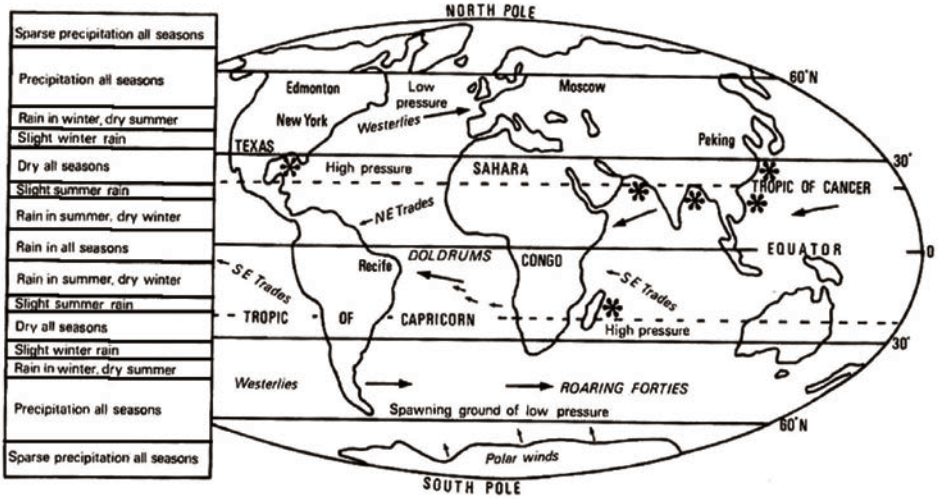


Fig. 2.1: Weather belts on the northern and southern hemispheres and hurricane and cyclone spots.

Surface temperature differences cause pressure differences. A hot surface heats the air above it and the air expands, lowering the air pressure. The resulting horizontal pressure gradient accelerates the air from high to low pressure, creating wind. Earth's rotation causes curvature of the flow via the Coriolis' effect. The simple systems thus formed can then display emergent behaviour to produce more complex systems and thus other weather phenomena. The strong temperature contrast between polar and tropical air gives rise to the jet stream. Most of the weather systems in the mid-latitudes are caused by instabilities of the jet stream flow. Weather systems in the tropics are caused by different processes, such as monsoons or organized thunderstorm systems. Over thousands to hundreds of thousands of years, changes in Earth's orbital parameters affect the amount and distribution of solar energy received by the Earth and influence in long-term. As the Earth's axis is tilted relatively to its orbital plane, sunlight is incident at different angles at different times of the year. In June the northern hemisphere is tilted towards the sun, so at any given northern hemisphere latitude sunlight falls more directly on that spot than in December (effect of sun angle on climate) and this effect causes seasons.

2.2 Tropical Activity

Tropical atmosphere is the heat engine driving many of the synoptic-scale weather systems in the middle and higher altitudes. The transfer of energy in the form of latent and sensible heat, water and water vapour from low to middle latitudes vented from even quite modest tropical weather systems at high levels in the form of cloud bands that is observed daily on geostationary satellite images. Convection at the small and meso-scale is the prime force which pumps the tropical atmosphere. The smallest convectional process (greatest surface heating accompanied by an almost parallel movement of the cellular convectional system) which are not a part of largest and better organized synoptic features are, therefore, not only mostly day-time phenomena – particularly over the continental areas – but they are also subject to pronounced seasonal variations in their location of occurrence. Tropical activity in general consists of large air masses several hundred miles across with low pressure at the centre and with winds blowing around the centre (Fig. 2.2) in either a clockwise direction (southern hemisphere) or counterclockwise (northern hemisphere). Precipitation arises when a warm front is formed by an advancing mass of warm air, which moves up an inclined surface of retreating cold air and is chilled in the process of being

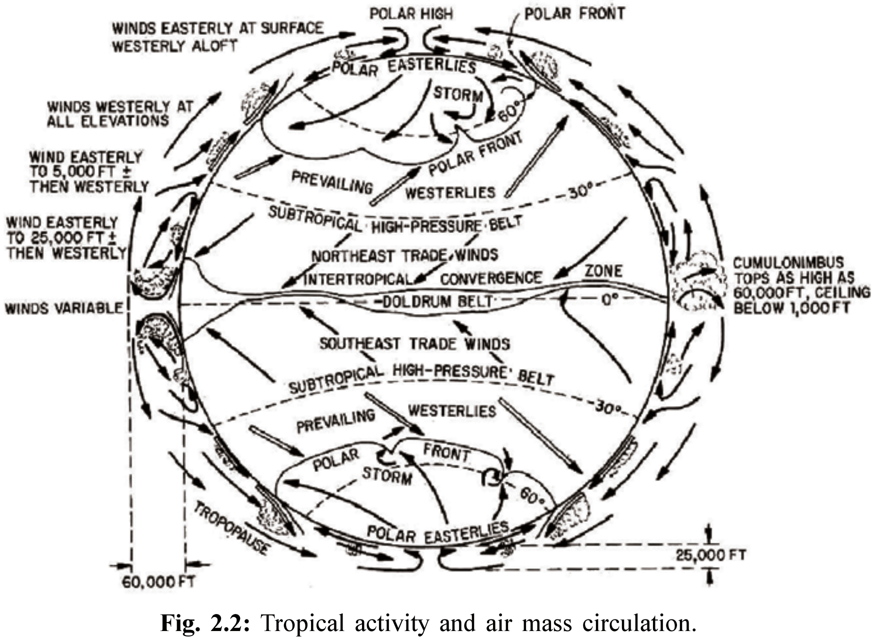


Fig. 2.2: Tropical activity and air mass circulation.

lifted up resulting in rainfall. The Great Sandy Desert has nearly all its rain from monsoonal thunderstorms or the occasional tropical cyclone rain depression. Due to the high rates of evaporation in deserts, this area remains an arid environment with vast stretches of sand. Other areas of the world which see these rare precipitation events in deserts are northwest Mexico, the southwestern United States, and southwest Asia. In North America, the Sonoran and Chihuahuan deserts have received some tropical rainfall in the last 10 years. Tropical activity is rare in all deserts, but whatever rain does arrive there is important to the existence of the delicate ecosystem.

Monsoon

Monsoon is a seasonal prevailing wind which lasts for several months. *Monsoon* is an Arabic word indicating season that relates specifically to a substantial change in wind direction, often through 180°, which brings with it a very distinctive change in weather type and precipitation amount. This term was first used in English in India, Bangladesh, Pakistan, and neighbouring countries to refer to the big seasonal winds blowing from the Indian Ocean and Arabian Sea in the southwest bringing heavy rainfall to the region. In hydrology, monsoon rainfall is considered to be that which occurs in any region that receives the majority of its rain during a particular season. This allows other regions of the world such as North America, South America, Sub-Saharan Africa, Australia and East Asia to qualify as monsoon regions. In terms of total precipitation and total area covered, the monsoons affecting the Indian subcontinent dwarf the North American monsoon. The South Asian monsoon affects a larger number of people due to the high density of population in this part of the world. The definition includes *major wind systems* that *change direction seasonally*. Most summer monsoons have a dominant westerly component and a strong tendency to ascend and produce copious amounts of rain (because of the condensation of water vapour in the rising air). The intensity and duration, however, are not uniform from year to year. Winter monsoons, by contrast, have a dominant easterly component and a strong tendency to diverge, subside, and cause drought.

Monsoons are caused by the larger amplitude of the seasonal cycle of land temperature compared to that of nearby oceans. This differential warming happens because heat in the ocean is mixed vertically through a "mixed layer" that may be fifty metres deep. The specific heat capacity of the layer participating in the seasonal cycle is much larger over the oceans than over land, with the consequence that the air over the land warms faster and reaches a higher temperature than the air over the ocean. The hot air over the land tends to rise, creating an area of low pressure. This creates a steady wind blowing towards the land, bringing the moist near-surface air over the oceans with it. Rainfall is caused by the moist ocean air being lifted upwards by mountains, surface heating, convergence at the surface, divergence aloft, or from storm-produced outflows at the surface. However as the lifting occurs, the air cools due to expansion in lower pressure, which in turn produces condensation.

In winter, the land cools off quickly, but the ocean keeps the heat longer. The hot air over the ocean rises, creating a low pressure area and a breeze from land to ocean while a large area of drying high pressure is formed over the land, increased by winter-time cooling. Monsoons are similar to sea and land breezes, a term usually referring to the localized, diurnal (daily) cycle of circulation near coastlines everywhere, but they are much larger in scale, stronger and seasonal. As monsoons have become better understood, the term monsoon has been broadened to include almost all of the phenomena associated with the annual weather cycle within the tropical and subtropical land regions of the earth. It is understood that in the geological past, monsoon systems must have always accompanied the formation of super-continents such as Pangaea, with their extreme continental climates. *Northeast Monsoon* (Southern Asia and Australia) – In Southern Asia, the northeastern monsoons take place from December to early March. The temperature over central Asia is less than 25°C as it is the northern hemisphere winter, therefore creating a zone of high pressure there. The jet stream in this region splits into the southern subtropical jet and the polar jet. The subtropical flow directs northeasterly winds to blow across southern Asia, creating dry air streams which produce clear skies over India. Meanwhile, a low pressure system develops over South-East Asia and Australasia and winds are directed towards Australia known as a monsoon trough.

The climate in India is broadly described as tropical monsoon type. The four seasons are: winter (January-February), a hot summer period (March-May), a rainy south-western monsoon period (June-September) and a north-eastern monsoon period (October-December). In addition, a number of micro-climatic patterns occur. The Kashmir valley and some other higher altitude regions experience a typical temperate climate, while still higher areas, such as Ladakh, Lahul and Spiti, have a typical cold-arid desert climate. India‘s climate is formed by the north-east monsoon (winter monsoon) winds which blow from land to sea and the south-west monsoon (summer monsoon) winds which blow from sea to land after crossing the Indian Ocean, the Arabian sea and the Bay of Bengal. Most rainfall in India is caused by the south-west monsoon. The southwestern summer monsoons occur from June through September. The Great Indian Desert (Thar Desert) and adjoining areas of the northern and central Indian subcontinent heat up considerably during the hot summers. This causes a low pressure area over the northern and central Indian subcontinent. To fill this void, the moisture-laden winds from the Indian Ocean rush in to the subcontinent. These winds, rich in moisture, are drawn towards the Himalayas, creating winds blowing storm clouds towards the subcontinent. However the Himalayas act like a high wall and do not allow the winds to pass into Central Asia, forcing them to rise. With the gain in altitude of the clouds, the temperature drops and precipitation occurs. Some areas of the subcontinent receive up to 10,000 mm of rain.

A delay of a few days in the arrival of the monsoon can, and does, badly affect the economy, as evidenced in the numerous droughts in India in the 90s. June 1 is regarded as the date of onset of the monsoon in India, which is the average date on which the monsoon strikes Kerala over the years.

North-East Monsoon (Retreating Monsoon) – Around September, with the sun fast retreating south, the northern land mass of the Indian subcontinent begins to cool off rapidly. With this air pressure begins to build over northern India. The Indian Ocean and its surrounding atmosphere still holds its heat. This causes the cold wind to sweep down from the Himalayas and Indo-Gangetic Plain towards the vast spans of the Indian Ocean south of the Deccan peninsula. This is known as the North-East Monsoon or Retreating Monsoon. While travelling towards the Indian Ocean, the dry cold wind picks up some moisture from the Bay of Bengal and pours it over peninsular India. Cities like Chennai, which gets less rain from the South-West Monsoon receives rain from the Retreating Monsoon. About 50-60% of the rain received by the state of Tamil Nadu is from the North-East Monsoon. It is worth noting that North-East Monsoon (or the Retreating Monsoon) is not able to bring as much rain as the South-West Monsoon.

North American Monsoon (NAM) occurs from late June or early July into September, originating over Mexico and spreading into the southwest United States by mid-July. It affects Mexico along the Sierra Madre Occidental as well as Arizona, New Mexico, Nevada, Utah, Colorado, West Texas, and California. It pushes as far west as the Peninsular Ranges and Transverse Ranges of southern California but rarely reaches the coastal strip (a wall of desert thunderstorms only a half-hour's drive away is a common summer sight from the sunny skies along the coast during the monsoon). The North American monsoon is known to many as the Summer, Southwest, Mexican or Arizona monsoon. It is also sometimes called the Desert Monsoon as a large part of the affected area is desert. *African Monsoon* of western sub-Saharan Africa is the result of the seasonal shifts of the Inter-tropical Convergence Zone and the great seasonal temperature differences between the Sahara and the equatorial Atlantic Ocean. It migrates northward from the equatorial Atlantic in February, reaches western Africa on June 22, then moves back to the south by October 15. The dry, northeasterly trade winds, and their more extreme form, the harmattan, are interrupted by the northern shift in the ITCZ and resultant southerly, rain-bearing winds during the summer. The semiarid Sahel and Sudan depend upon this pattern for most of their precipitation. *South American Monsoon:* Much of Brazil experiences seasonal wind patterns that bring a summer maximum to precipitation. Rio de Janeiro is infamous for flooding as a result of monsoon rains.

Precipitation processes involve: (1) Pre-monsoonal convectional storms and squall lines, produced by the release of potential instability and with the first heating of the lower layers of the atmosphere at a time when dry, cool air dominates above; (2) Storms produced at the leading edge of the moist air from the Indian Ocean – Inter-tropical front; (3) Pronounced orographic effect in certain areas triggering thunderstorms by the release of circulation associated with temporary invasions of the northern temperate westerlies (Pant, 1981) which tends to weaken the monsoon circulation and reduce precipitation activity and with the formation and movement of monsoon depressions from the Bay of Bengal steered northwestwards by the upper airflow; (4) Short-term changes in the sea surface temperature of the Arabian Sea/Indian Ocean areas are apparently indicators of overall monsoon rainfall (Pisharoty, 1981). Further, the moist oceanic airflow is extremely shallow and is often overlain by dry, subsident air, which inhibits any pronounced convectional cloud or precipitation; and (5) The surface position of the migrating monsoon trough is strongly influenced by continental heating in the summer months bringing moist southwesterlies.

2.3 Precipitation Type

Stratiform or *dynamic precipitation* occurs as a consequence of slow ascent of air in synoptic systems, such as along cold fronts, and in advance of warm fronts. *Convection rain* or *showery precipitation* occurs from convective clouds, e.g., cumulonimbus or cumulus congestus. It falls as showers with rapidly changing intensity. Convective precipitation falls over a certain area for a relatively short time, as convective clouds have limited horizontal extent. Most precipitation in the tropics appears to be convective; however, it has been suggested that stratiform precipitation also occurs. Graupel and hail always indicate convection. In mid-latitudes, convective precipitation is associated with cold fronts (often behind the front), squall lines, and warm fronts with significant available moisture. *Orographic precipitation* occurs on the windward side of mountains and is caused by the rising air motion of a large-scale flow of moist air across the mountain ridge, resulting in adiabatic cooling and condensation.

In mountainous parts of the world subjected to relatively consistent winds (for example, the trade winds), a more moist climate usually prevails on the windward side of a mountain than on the leeward (downwind) side. Moisture is removed by orographic lift, leaving drier air on the descending (generally warming), leeward side where a rain shadow is observed. Orographic precipitation is well known on oceanic islands, such as the Hawaiian Islands, where much of the rainfall received on an island is on the windward side, and the leeward side tends to be quite dry, almost desert-like, by comparison. This phenomenon results in substantial local gradients of average rainfall, with coastal areas receiving on the order of 500 to 750 mm per year (20 to 30 inches), and interior uplands receiving over 2.5 m per year (100 inches). Leeward coastal areas are especially dry 500 mm per year (20 inches) at Waikiki, and the tops of moderately high uplands are especially wet – ~12 m per year (~475 inches) at Wai'ale'ale on Kaua'i. In South America, the Andes mountain range blocks most of the Atlantic moisture that arrives in that continent, resulting in a desert-like climate on the Pacific coast of Peru and northern Chile, since the cold Humboldt Current ensures that the air off the Pacific is dry as well. On the leeward side of the Andes is the Atacama Desert of Chile. It is also blocked from moisture by mountains to its west as well. Not coincidentally, it is the driest place on earth. The Sierra Nevada range creates the same effect in North America forming the Great Basin desert, Mojave Desert and Sonoran Desert.

2.4 Weather Forecast

Weather forecasts are made by collecting data that describe the current state of the atmosphere (particularly the temperature, humidity and wind) and using physically-based mathematical models to determine how the atmosphere is expected to change in the future. The chaotic nature of the atmosphere means that perfect forecasts are impossible, and that forecasts become less accurate as the range of the forecast increases. It is carried out from information collected from network of observation stations. During mid 1950s, all weather maps and charts were plotted by hand and analyzed by individuals based on certain developed thumb rules for different systems. The present-day forecasts use modern electronic computers that could handle large quantities of data. Meteorologists interpret the weather patterns and final chart is referred to as an analysis. The routine daily forecasting of weather by the computer is known as *numerical weather prediction*. As the weather variables are constantly changing, meteorologists have devised atmospheric models that describe the present state of the atmosphere. These mathematical equations describe how atmospheric temperature, pressure, winds and moisture will change with time. They do not fully represent the real atmosphere but retain the important aspects of atmospheric behaviour.

Forecast question	*Use of forecast chart*
Cloudy or clear	On the 700-mb forecast chart, the 70% relative humidity line usually encloses areas that are likely to have clouds.
Will it rain	On the 700-mb forecast chart, the 90% relative humidity line often encloses areas where precipitation is likely. If upward velocities are present, the chance of measurable precipitation is enhanced.
Will it rain or snow	On the 850-mb forecast chart, snow is likely north of the –5°C (23°F) isotherm whereas rain is likely south of this line.

Advanced Weather Interactive Processing System (AWIPS) is a computer module that handles charts and maps in forecast. It has data communication, storage, processing and display capabilities (including graphical overlay). Forecast models predict the weather reasonably well 4 to 6 days into the future. Their accuracy tends to a better job at predicting temperature and jet-stream patterns than precipitation. Two distinct approaches have been adopted for generating predictions for seasonal rainfall. In the traditional approach, empirical models based on analysis of historical data of the variability of monsoon and its relation to a variety of atmospheric and oceanic variables over different parts of the world prior to the summer monsoon season are used. In the second approach predictions are generated by physical models based on the equations governing the physics of the atmosphere from an initial state prior to the season. The empirical models used operationally by Indian Meteorology Department (IMD) since 1932, based on the relationship of the monsoon rainfall to atmospheric/oceanic conditions over different parts of the globe, have not produced any satisfactory results. Atmospheric and coupled models in predicting the Indian monsoon rainfall are also not satisfactory and the problem is particularly acute as these models fail to predict the extremes such as drought and excess rainfall seasons (Sulochana Gadgil et al., 2005).

Methods

Persistence forecast predicts that future weather will be the same as present weather. It is most accurate for time periods of several hours and become less accurate after that. *Steady-state* or *Trend method* considers that surface weather system tends to move in the same direction and at approximately the same speed as they have been moving, provided no evidence exists to indicate otherwise. We could extrapolate and predict when the front would pass through your area – three hours or so. *Analogue method* relies on that existing features on a weather chart strongly resemble features that produced certain weather conditions in the past. As the forecaster relies on the “looks familiar” pattern on the weather chart, it is also called as *pattern recognition method*. The weather situation may appear similar but not exactly the same with sufficient differences in variables. *Statistical forecast* are made routinely of weather elements based on the past performance of computers – MOS (Model Output Statistics). Forecast calling for rain @ 60% indicate that any random place in the forecast area will receive measurable rainfall. Probability forecast uses 30 years of data and gives the likelihood of rain or snow in terms of probability.

Percent probability of precipitation	*Forecast wording for steady precipitation*	*Forest wording for showery precipitation*
20%	Slight chance of precipitation	Widely scattered showers
30-50%	Chances of precipitation	Scattered showers
60-70%	Precipitation likely	Numerous showers
> 80%	Precipitation (rain or snow)	Showers

Weather prediction employs the analogue method. Weather patterns are categorized into similar groups or types using such criteria as the position or the subtropical highs, the upper-level flow and the prevailing storm track.

Forecast Types

National meteorological departments/organizations continuously monitor atmosphere, cloud, temperature and pressure conditions of the atmosphere and forecast the rainfall or snow or high winds etc. They indicate the anticipated conditions within hours to days. Weather forecast issued from Indian Meteorological Department and National Center for Medium Range Weather Forecasting (NCMRWF) as Farmers weather bulletin, Agro meteorological Advisory Bulletin (Short range forecast – 24 to 48 hrs) for operational decisions. Farm operations with optimal costs and reduced expenditure related to planting, watering, pest control, harvesting, storage and marketing. It contains expected cloudiness, probability of rain and rainfall, dew duration and intensity and range of high and low temperature. Weather forecast for up to a few hours (usually not more than six hours) is called *very-short-range forecast* or *nowcast*. It is done using subjective interpretations of surface observations, satellite imagery and Doppler radar information, when weather systems are moved along by the steady state or trend. Weather forecasts that range from six hours to few days (generally 2.5 days or 60 hours) are called *short-range forecasts*. Satellite imagery, Doppler radar, surface weather maps, upper-air winds and pattern recognition are incorporated in this. As forecast period extends beyond about 12 hours, the forecasters tend to weigh the forecast heavily on computer drawn progs and statistical information such as Model Output Statistics (MOS).

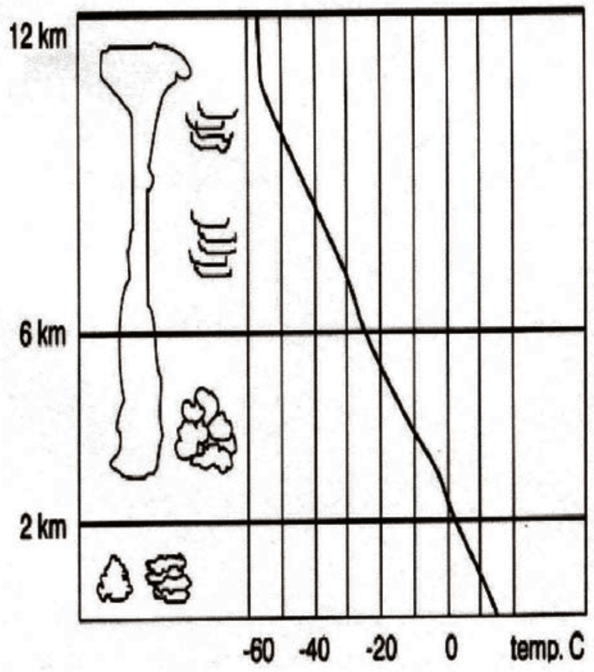
Medium range forecast are issued prior to 3 to 10 days for planning agriculture operations. A medium-range forecast extends from 3 to 8.5 days (200 hours) into future based only on computer-derived products (Progs and

MOS). A forecast that extends beyond three days is often called *extended forecast*. *Long range forecast* – 11 days to season – contains information on seasonal rainfall in advance in deciding cropping pattern, food and fodder storage, reservoir regulations etc. They extend beyond 8.5 days (200 hours). Computer Prognostic charts (charts showing expected or forecasted conditions such as pressure pattern, frontal positions, contour height pattern and so on) available for upto 16 days into the future are not accurate in predicting temperature and precipitation and offers broad-scale weather features. The operational models utilize power regression methods using parameters – Arabian Sea surface temperature, Eurasian snow cover, Northwest Europe mean temperature, Nino 3 SST, South Indian Ocean SST Index, East Asia pressure, Europe pressure gradient and 50 hpa wind pattern. Probabilistic models estimate rainfall in categories: Deficient (<90% of LPA); Below normal (90-98% of LPA); Near normal (98-102% LPA); Above normal (102-110% of LPA); and Excess (>110% of LPA). Average weather conditions for particular month or season is given by *outlook*, which are overview of average precipitation and temperature pattern assuming a normal condition. It is based on the projected average upper-air flow and the surface weather conditions that the type of flow will create. There is no clear-cut method in determining the forecast accuracy. Irrespective of the complexity and ever-changing nature of the atmosphere, forecast made for between 12 and 24 hrs are quite accurate, 2 and 5 days are fairly good and beyond seven days, accuracy drops down due to chaotic nature of atmosphere. Long-term mean rainfall gives a general picture of the water potential for crop production in spite of the substantial year-to-year variation in rainfall. Rainfall probability of occurrence is important in assessing the long-term suitability of crop cultivators and crop management strategies. Advances in medium-term weather forecasting offers hope in within-season adjustments (Meinke et al., 2001). A period of only a few weeks without precipitation may lead to agriculture productivity. Assessing drought severity requires a measure of effective rainfall in relation to soil moisture and plant condition, rather than just summing rainfall deficiencies (Wilhite and Glantz, 1985).

Forecasts go awry due to: (1) Computer models idealize the real atmosphere by making certain assumptions about the atmosphere, (2) Most of the models are not global in their coverage and errors are likely to creep along the model boundary, (3) Irrespective of weather observations, there are still regions where the observations are sparse in higher altitude areas, (4) Most of the computer models cannot adequately interpret factors that influence surface weather such as interactions of water, ice, surface frictions and local terrain on weather system, (5) MM5 model (developed by National Center for Atmospheric Research and Pennsylvania university) has a grid space as low as 4 km, while others miss those information, (6) Computer models that forecast for large areas do not predict local weather conditions such as temperature, winds and precipitation, (7) Unpredictable atmospheric fluctuations (chaos) go unrepresented in the models, and (8) Ensemble forecasting technique used in medium-range forecasts tweak a bit of the initial conditions of observation leading to deviations over a repeated run, etc.

2.5 Clouds

Without clouds there would be no rain or snow. It is a visible aggregate of tiny water droplets or ice crystals suspended in the air. It can be thick or thin, big or little; they exist in a seemingly endless variety of forms. Figure 2.3 shows the cloud types and the temperature at different elevation in the atmosphere. They are classified into basic types and their approximate base height at tropical region are shown below:



High clouds
Composed primarily of Ice.
Appears white on IR imagery.

Cumulonimbus appears as bright white patches. Associated with thunder storm activity.

Cirrus cloud appears as bright white streaks.

Middle cloud
Appear in lighter shade on IR images.
Altocumulus have mottled texture
Altostratus appeasr as sheet like. They are sandwiched between low & high clouds. Distinct level identification difficult

Low clouds
Lowest clouds are stratus and fog.
On IR image it appears as dark shades and lack texture.

Fig. 2.3: Cloud types and the temperature at different levels.

High clouds (6000-18000 m)	*Middle clouds (2000-8000 m)*	*Low clouds (0 – 2500m)*	*Clouds with vertical development*
Cirrus (Ci)	Altostratus (As)	Stratus (St)	Cumulus (Cu)
Cirrostratus (Cs)	Altocumulus (Ac)	Stratocumulus (Sc)	Cumulonimbus (Cb)
Cirrocumulus (Cc)		Nimbostratus (Ns)	

Cloud Identification

High clouds appear white, except near sunrise and sunset. Components of the sun lights are reflected from the underside of the clouds. They are composed of exclusively ice crystals and are also thin. *Cirrus* (Ci) clouds are thin, wispy clouds blown by high winds into long streamers called Mare's trail and looks like a white feathery patch with a faint wisp of a tail at one end. *Cirrocumulus* clouds seen less frequently are small rounded white puffs that may occur individually or in long rows. It has a rippling appearance. *Cirrostratus* clouds are thin, sheet like high clouds and moon and sun can be seen through them. The ice crystals in these clouds refract the light passing through them. Thick cirrostratus clouds give the sky a glary white appearance and frequently form ahead of an advancing storm; hence they are used to predict rain or snow within 12 to 24 years, especially if they are followed by middle type clouds. *Middle clouds* are composed of water droplets and when temperature becomes low enough-some ice crystals. *Altocumulus* clouds are composed mostly of water droplets and rarely more than 1 km thick. They appear as gray, puffy masses, sometimes rolled out in parallel waves or bands. Little castle appearance indicates the presence of rising air at cloud level. The appearance of these clouds on a warm humid summer morning often portends thunderstorm by evening. *Altostratus* is a gray or blue-gray cloud composed of ice crystals and water droplets. It covers the entire sky extending over 100s of square kilometres. Gray colour, height and dimness of the sun are clues to identify altostratus. It forms ahead of storms having widespread and relatively continuous precipitation. If precipitation falls from altostratus, its base usually lowers. If the precipitation reaches the ground, the cloud is then classified as *Nimbostratus*. Intensity of precipitation is light or moderate and never heavy and only showery.

Low clouds are composed of water droplets and ice particles and snow in cold weather. *Nimbostratus* is usually darker gray than thick altostratus and you cannot see the sun or moon through this layer because rain will evaporate and mix with the air in this region. As the clouds drift rapidly with the wind, they form irregular shreds with a ragged appearance and are called as stratus fractures or scud. *Stratocumulus* are low lumpy clouds that appear in rows in patches or as round masses with blue sky visible between the individual cloud elements. Precipitation rarely falls from this clouds, showery precipitation may occur in winter if the cloud element develops vertically into much large cloud and their tops grow colder than about –5°C. *Stratus* is a uniform grayish cloud that often covers the entire sky and resembles a fog that does not reach the ground. No precipitation falls from the stratus, but sometimes it is accompanied by a light mist or drizzle. *Clouds with vertical development:* The puffy *cumulus* cloud takes on a variety of shapes but often it looks like a piece of floating cotton with sharp outlines and a flat base appears as white to light gray. The top of the cloud appears to be in the form of rounded towers denoting the limit of rising air and not very high. Cumulus clouds that show only slight vertical growth are called *cumulus humilis* and are associated with fair weather. Ragged edge cumulus clouds are smaller than cumulus humilis, scatter across the sky and are called cumulus fractus. *Cumulus congestus* or towering cumulus resembles like a cauliflower indicating larger and vertically developed. As they grow vertically, they develop into a giant *cumulonimbus* – a thunderstorm cloud. It can occur as an isolated cloud or as part of a line or wall of clouds. Tremendous amount of energy released by the condensation of water vapour within a cumulonimbus result in the development of violent up and downdrafts which may exceed 70 knots. Lightning, thunder and even violent tornadoes are associated with the *cumulusnimbus*. Occasionally soft pearly looking clouds seen above troposphere above 30 km are called *nacreous clouds*. They appear to be composed of water either in solid or liquid (super cooled) form. Summary of the clouds observed from the ground is shown in Fig. 2.4 (a and b). Eye-observations of the current weather situation including estimation of cloud parameters (cloud amount, cloud depth, cloud type, cloud-base height) are performed 3-hourly at the main automatic climate stations, 4-hourly at

Name: Cumulus
Altitude: < 2 km
Composition: Water
Temperature: 5° to 15° C

Name: Fog
Altitude: < 5000 ft.
Composition: Water
Temperature: 10° to 20° C

Name: Stratus
Altitude: < 2 km
Composition: Water
Temperature: 5° to 15° C

Fig. 2.4(a): Cloud types and their identifiable shapes.

Name: Cirrus
Altitude: < 6 km
Composition: Ice crystals
Temperature: -50° to -60° C

Name: Cumulus congestus
Altitude: 6 km
Composition: Water
Temperature: -10° to -20° C

Name: Cumulonimbus
Altitude: 12 km
Composition: Water and ice
Temperature: -50° to -60° C

Fig. 2.4(b): Cloud types and their identifiable shapes.

the aero stations and 6-hourly at all other climate stations of the Swiss Meteorological Institute (SMI). It is important to note that these observations are sometimes done by different persons at the same station so that the subjectivity of the estimated values is not only between stations but also within the time series of one station.

Cloud Observation

Weather predictions can be made by observing the sky using little weather wisdom. Little practice will be able to make fairly good short-range local weather forecasts by interpreting the messages written in the weather elements. Movements of clouds at different levels can assist us in predicting change in the temperature of the air above you and the stability of air mass. By observing the movement of cloud mass on successive satellite images, the forecaster can predict its arrival time and hence, when rainfall will begin. Descriptions of sky conditions are defined by the fraction of sky covered by cloud. Description of the sky by meteorologists is given below:

Description	*ASOS*	*Human*	*Meaning*
Clear (CLR or SKC)	0 to 5%	0	No clouds
Few	>5 to <25%	0 to 2/8	Few clouds
Scattered (SCT)	> 25% to < 50%	3/8 to 4/8	Partly cloud
Broken (BKN)	> 50 to 87%	5/8 to 7/8	Mostly clouds
Overcast (OVC)	> 87 to 100%	8/8	Sky is covered by clouds
Sky obscured	-	-	Sky hidden by surface based phenomena such as fog, blowing snow, smoking and so forth rather than cloud cover

ASOS – Automated Surface Observation System

In addition to the human and Automated Surface Observation System (ASOS), weather observations are carried out by geostationary weather satellites. They orbit the equator at the same rate the earth spins and remains at nearly 36,000 km above a fixed spot on the surface. They use a real time data system to transmit images to the ground receiving stations. Successive cloud information can be put into a time-lapse movie sequence to show the cloud movement, dissipation or development associated with weather fronts and storms. Wind directions and speed at various levels may also be approximated by this data. Polar orbiting satellites (above 850 km) have the advantage of photographing clouds directly beneath them and provide sharp features. Geostationary images are slightly distorted because of the low angle at which the satellite sees this region. In *Conventional synoptic method*, forecasting tools like trend, persistence, climatology, and analogue of weather systems are popularly employed. Each of these methods makes use of some basic assumptions for extrapolating the weather into the future. The forecaster blends these extrapolations with his own experience and the location specific weather quirks like topography, land sea distributions etc. Weather charts prepared by the meteorological departments are extensively used by pilots of air lines, crop watch groups and agriculture extension groups. Legend information related to weather symbols (Fig. 2.5), clouds and coverage (Fig. 2.6) and wind speed (Fig. 2.7) are important.

2.6 Cloud Mapping – Satellite

The first weather satellite, Vanguard 2, was launched on 17 February 1959. It was designed to measure cloud cover and resistance, but a poor axis of rotation kept it from collecting a notable amount of useful data. The first weather satellite to be considered a success was TIROS-1, launched by NASA on 1 April 1960. TIROS operated for 78 days. TIROS-1, used television cameras to photograph clouds. Successive satellites used radiometers that

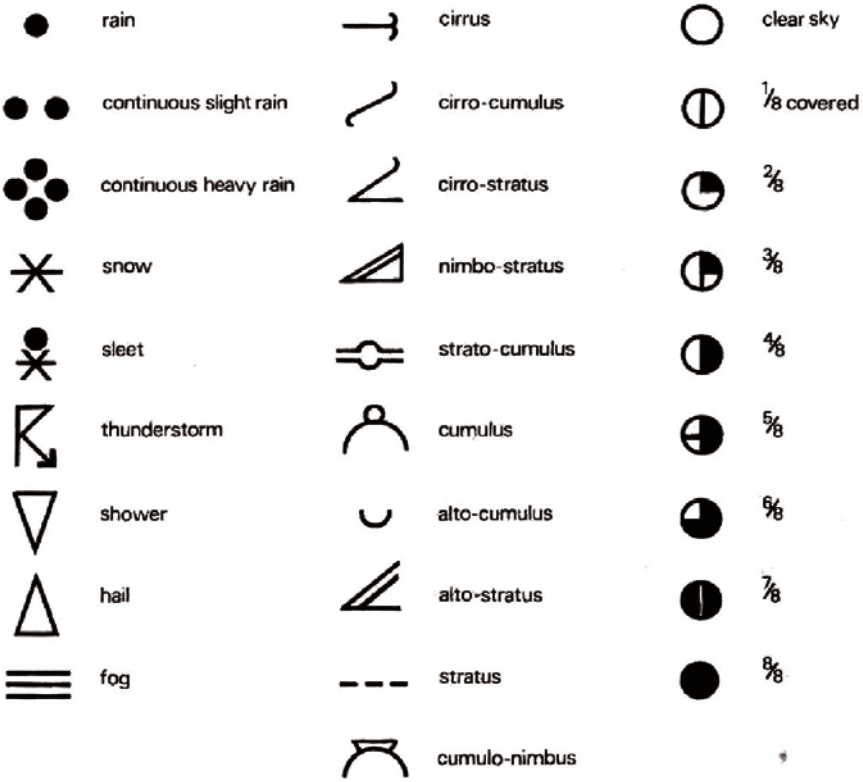
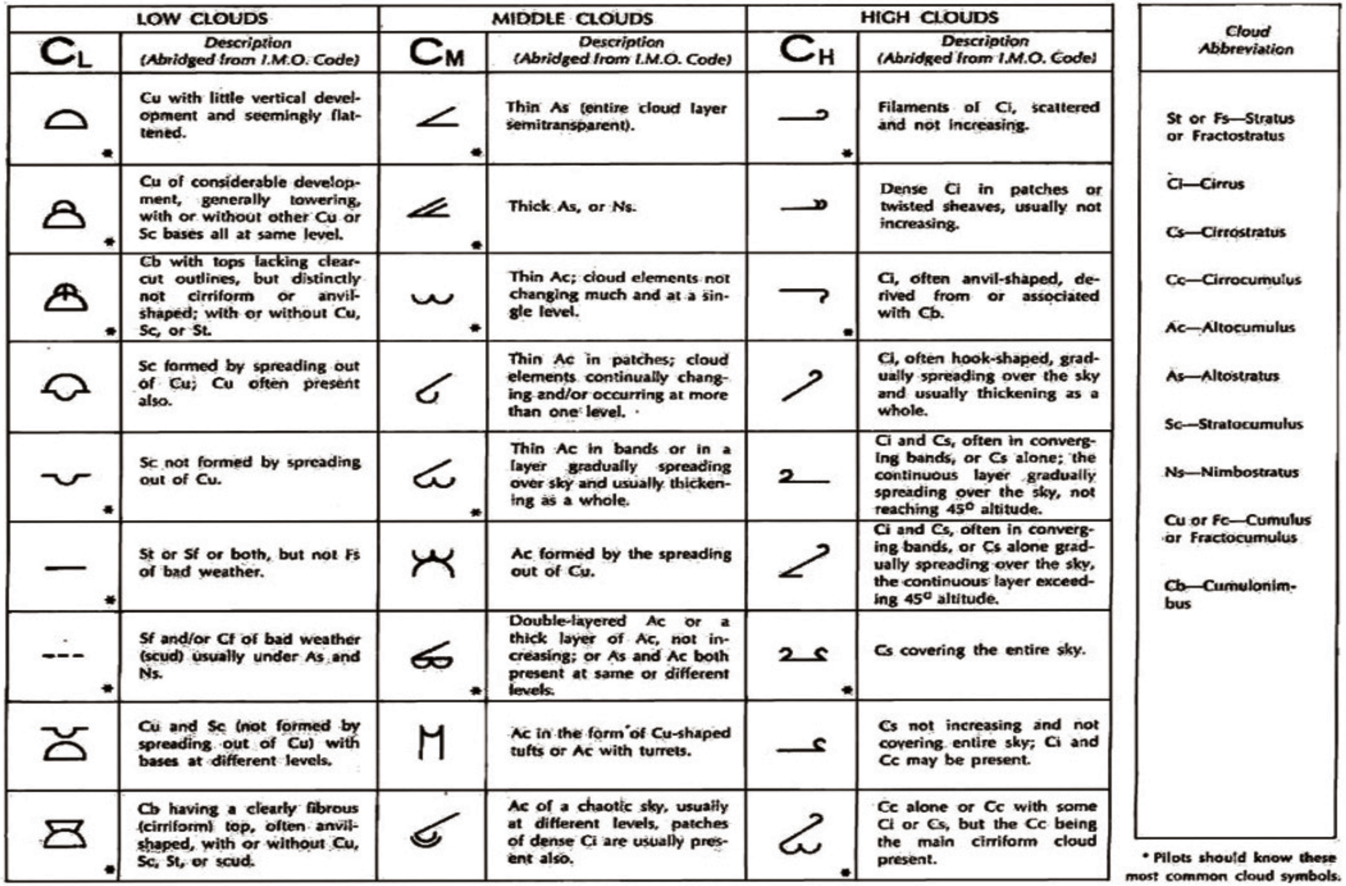


Fig. 2.5: Weather symbols and their use.

can observe clouds during both day and night by detecting radiation that emanates from the top of the clouds. Several geostationary meteorological spacecrafts are in operation. The United States has two in operation: GOES-11 and GOES-12. GOES-12 is designated GOES-East, over the Amazon River and provides the U.S. weather information. GOES-11 is GOES-West over the eastern Pacific Ocean. Geostationary Operational Environmental Satellites (GOES) have the capacity to obtain cloud images and also vertical profiles of atmospheric temperature and moisture by detecting emitted radiation from atmospheric gauges – water vapour. Imager radiometers provide best digital picture and sounder gives more accurate profile of temperature and moisture at different levels in atmosphere than the earlier ones. The Japanese have one in operation; MTSAT-1R over the mid Pacific at 140°E. The Europeans have Meteosat-8 (3.5°W) and Meteosat-9 (0°) over the Atlantic Ocean and have Meteosat-6 (63°E) and Meteosat-7 (57.5°E) over the Indian Ocean. The Russians operate the GOMS over the equator south of Moscow. India also operates geostationary satellites which carry instruments for meteorological purposes. China operates the Feng-Yun geostationary satellites, FY-2C at 105°E and FY-2D at 86.5°E.



LOW CLOUDS		MIDDLE CLOUDS		HIGH CLOUDS	
C_L	*Description (Abridged from I.M.O. Code)*	C_M	*Description (Abridged from I.M.O. Code)*	C_H	*Description (Abridged from I.M.O. Code)*
*	Cu with little vertical development and seemingly flattened.	*	Thin As (entire cloud layer semitransparent).	*	Filaments of Ci, scattered and not increasing.
*	Cu of considerable development, generally towering, with or without other Cu or Sc bases all at same level.	*	Thick As, or Ns.		Dense Ci in patches or twisted sheaves, usually not increasing.
*	Cb with tops lacking clear-cut outlines, but distinctly not cirriform or anvil-shaped; with or without Cu, Sc, or St.	*	Thin Ac; cloud elements not changing much and at a single level.	*	Ci, often anvil-shaped, derived from or associated with Cb.
	Sc formed by spreading out of Cu; Cu often present also.		Thin Ac in patches; cloud elements continually changing and/or occurring at more than one level.		Ci, often hook-shaped, gradually spreading over the sky and usually thickening as a whole.
*	Sc not formed by spreading out of Cu.	*	Thin Ac in bands or in a layer gradually spreading over sky and usually thickening as a whole.		Ci and Cs, often in converging bands, or Cs alone; the continuous layer gradually spreading over the sky, not reaching 45° altitude.
*	St or Sf or both, but not Fs of bad weather.		Ac formed by the spreading out of Cu.		Ci and Cs, often in converging bands, or Cs alone gradually spreading over the sky, the continuous layer exceeding 45° altitude.
*	Sf and/or Cf of bad weather (scud) usually under As and Ns.	*	Double-layered Ac or a thick layer of Ac, not increasing; or As and Ac both present at same or different levels.	*	Cs covering the entire sky.
	Cu and Sc (not formed by spreading out of Cu) with bases at different levels.		Ac in the form of Cu-shaped tufts or Ac with turrets.		Cs not increasing and not covering entire sky; Ci and Cc may be present.
*	Cb having a clearly fibrous (cirriform) top, often anvil-shaped, with or without Cu, Sc, St, or scud.		Ac of a chaotic sky, usually at different levels, patches of dense Ci are usually present also.	*	Cc alone or Cc with some Ci or Cs, but the Cc being the main cirriform cloud present.

Cloud Abbreviation
St or Fs—Stratus or Fractostratus
Ci—Cirrus
Cs—Cirrostratus
Cc—Cirrocumulus
Ac—Altocumulus
As—Altostratus
Sc—Stratocumulus
Ns—Nimbostratus
Cu or Fc—Cumulus or Fractocumulus
Cb—Cumulonimbus

* Pilots should know these most common cloud symbols.

Fig. 2.6: Weather chart legend on clouds and coverage.

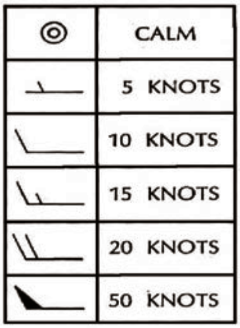


Fig. 2.7: Weather chart legend on wind speed.

The United States has the NOAA series of polar orbiting meteorological satellites, presently NOAA 17 and NOAA 18 as primary spacecrafts, NOAA 15 and NOAA 16 as secondary spacecrafts, NOAA 14 in standby, and NOAA 12. Europe has the Metop-A satellite and Russia, the Meteor and RESURS series of satellites. China and India have polar orbiting satellites as well. NOAA's polar orbiting satellites pass over the poles at approximately 850 km. They follow nearly fixed orbits while the earth rotates beneath them. The swaths are usually about 2600 km wide, and by completing 14 orbits a day one satellite can provide a complete cover of the globe twice every 24 hours. The area scanned by each pass (swath) is nearly adjacent at the equator on consecutive passes and polewards the passes progressively overlap. The radiometer points continuously at the earth (Earth Stabilized) and images are built up by a mirror on the satellite scanning from side to side at right angles to the orbit path. High Resolution Picture Transmission (HRPT) data is transmitted continuously and can be picked up at reception sites within range of the satellite. Reduced resolution Global Area Coverage (GAC) data is stored for later transition to NOAA. China launched Feng Yun-1D (FY-1D) on 15 May 2002. FY-1D is a polar-orbiting satellite, which means that during its orbit around the earth it (almost) overpasses the North and South poles. On board the satellite is an instrument called a Multi-channel Visible and Infrared Scan Radiometer (MVISR) which has 10 channels. Four of these channels are in the visible region of the electromagnetic spectrum, three in the near infrared, one in the short infrared and two in the long infrared. The spatial resolution of the instrument is 1.2 km. The Bureau of Meteorology receives FY-1D data around six times per day. This is enough data to provide a complete coverage of Australia once per day. China launched its latest geostationary meteorological satellite, Feng Yun-2B (FY-2B), on 25 June 2000 via a Long March-3 rocket from the Xichang Launching Centre, Sichuan Province, China. The satellite is located above the equator at 36,000 km altitude at longitude 105° East and commenced transmissions in January 2001. The satellite provides hourly full-disk images of the Earth in visible and infrared wavelengths.

Geostationary satellites such as MTSAT-1R (MTSAT-1R is operated by the Japan Meteorological Agency) orbit around the earth over the equator at a height of approximately 36,000 km. They complete one orbit every 24 hours so that their period is synchronised with that of the earth's rotation about its own axis. They therefore remain over the same location on the equator (stabilized by spinning rapidly). With this system images are built up by scanning with a mirror that is tilted in small successive steps from the north pole to south pole at a rate such that on each rotation of the satellite an adjacent strip of the earth is scanned. It takes 25 minutes to scan the full earth's disk. This builds a picture 10,000 pixels square for the visible images (1.25 km resolution) and 2500 pixels square (5 km resolution) for the infrared and water vapour images. The imagery is used in real time analysis and forecasting (for example, displaying the imagery directly in hourly loops) and the radiances information for global and meso-scale Numerical Weather Prediction (NWP) models. The current (real time) MTSAT-1R data and previous GMS and GOES-9 data are archived in McIdas format. McIdas stores the data as individual area files (Visible – approximately 450 Mbytes; Infrared Channel 4, Infrared Channel 5, Near Infrared Channel 2 and Infrared Channel 3 (Water Vapour) – approximately 30 Mbytes each) at full resolution. The GMS5 data was also archived in ASDA format as a 110 Mbyte file in a format as close to the original format as practicable.

Satellite imagery provides potential solution to the monitoring of large-scale systems such as super cell thunderstorms, depressions, cyclones, or meso-scale convective complex, particularly those in remote areas where there are sparse number of weather stations. The movement and patterns of clouds, observed from satellite images, can be used to indicate the instability of the weather. Moreover, useful information about rain clouds can be derived or inferred: cloud depth, cloud droplet size from visible (VIS) channels, cloud top temperature and height from infrared (IR) channels, and cloud phase from water vapour (WV) channels. Polar-orbiting satellites provide total precipitable water or cloud liquid water data at microwave (MW) wavelengths, which are precipitation-sensitive. We can practically relate rainfall to those satellite images by their appearance – brightness, texture, area, shape, organization and shadow of cloud – and motion of clouds provide information on rain movement. Each cloud type produces different amounts and types of rain e.g. stratiform clouds, which have small vertical velocities, produce low rain rates but widespread (~100 km) whereas convective clouds which have intermittently strong vertical velocities (> 1 m/s) give high rain rates (>5 mm/h) and intensity. Thus, the significant process of rain estimation is to select image features that can distinguish these two groups of clouds and then determine the relationship between these features and rain rate. Due to the high correlation between cloud motion and how rain moves, cloud motion vectors can be added to predict rainfall. In operational process, atmospheric motion vector (AMV) can be derived using cross-correlation techniques, which search for the best match of an object-of-interest in the target area. However the result is a displacement, not the velocity in 3D space. To obtain the velocity, optical flow techniques which apply a fluid dynamics constraint to the search can be used. In addition, the spiral movement equation can be added to improve the motion vectors.

Observation is typically made in the electromagnetic spectrum – Visible and infrared portions. Some of these channels include Visible and Near Infrared: 0.6 µm-1.6 µm; for recording cloud cover during the day; Infrared: 3.9 µm-7.3 µm (water vapour), 8.7 µm-13.4 µm (thermal imaging). Additional channels in the ultraviolet (100-400 nm) to microwave regions (0.15 to 6.0 cm) are also available. Kalpana satellite (also known as INSAT) images showing cloud coverage over India and adjoining areas are shown in Figs 2.8 (Visible band), 2.9 (IR), 2.10 (Water vapour), 2.11 (colour composite) and 2.12 (wind direction). The objective of image interpretation is to detect and identify features such as clouds or other obscuring or radiating phenomena on the image and determine the physical mechanisms that produce or sustain those features. Radiance measurements are taken along each scan line at time steps which produce a series of elements along that scan. They are referred as pixel element. The resolution of meteorological satellite instruments is at the rate of one km. Visible band (0.4-0.7 µm) in GOES offers the highest spatial resolution information on land, clouds and oceans. In the infra red channel (10-12.5 µm), the atmosphere is relatively transparent to radiation upwelling from the earth's surface. IR radiation can be related to the temperature of the emitting body and because the troposphere generally cools with height. This helps us to interpret the atmospheric process occurring within the scene: normally the image processing activities. It is said that greater the radiance brighter the pixel. Larger the radiance from an element,

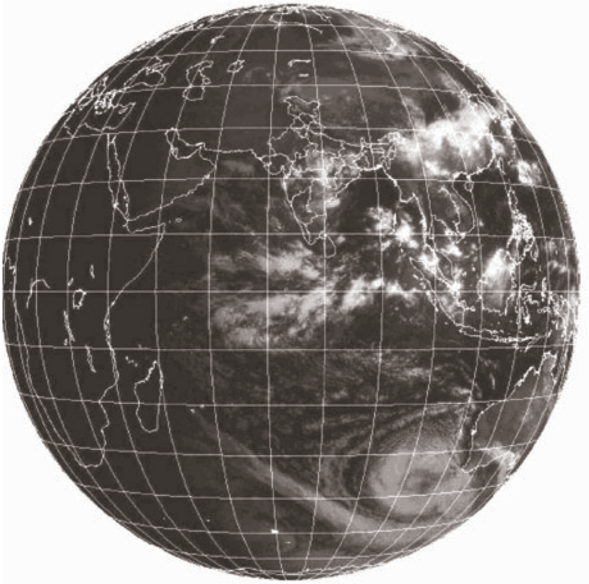


Fig. 2.8: Kalpana climate satellite image showing global environs in visible band.
(*Courtesy:* Indian Meteorology Department)

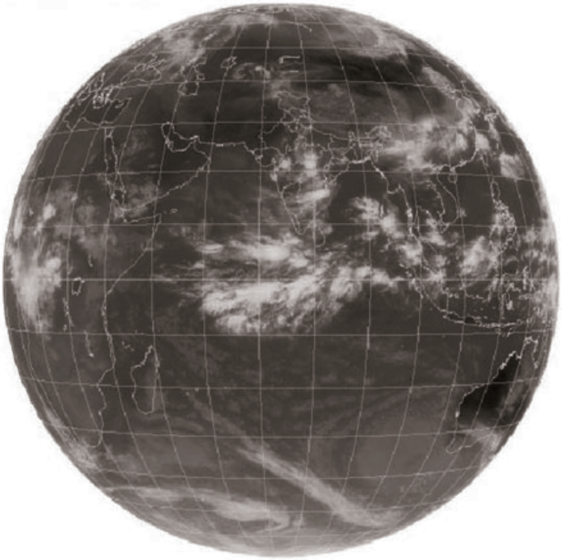


Fig. 2.9(a): Kalpana climate satellite image showing globe and its environs in IR band.

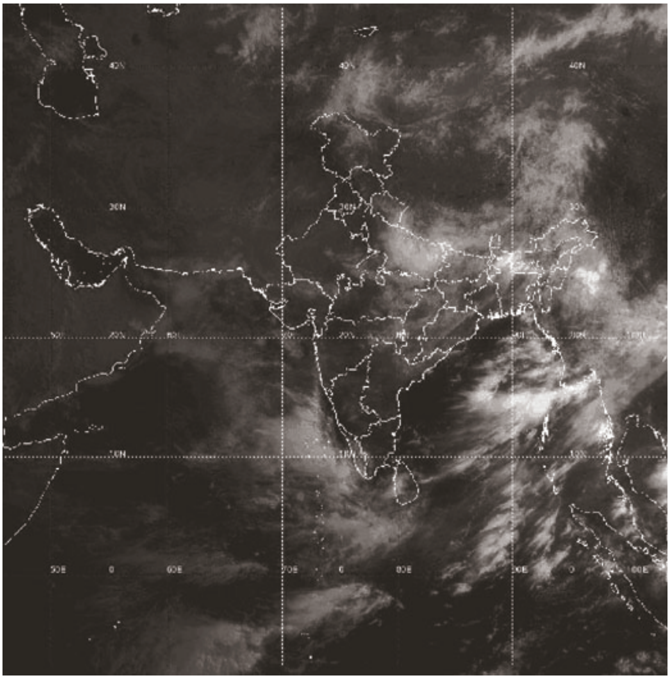


Fig. 2.9(b): Kalpana climate satellite image showing India and its environs in IR band.
(*Courtesy:* Indian Meteorology Department)

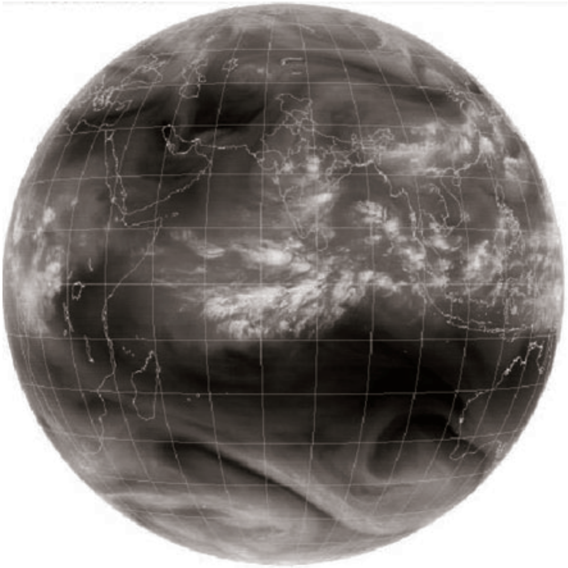


Fig. 2.10(a): Kalpana climate satellite image showing globe and its environs in water vapour band.

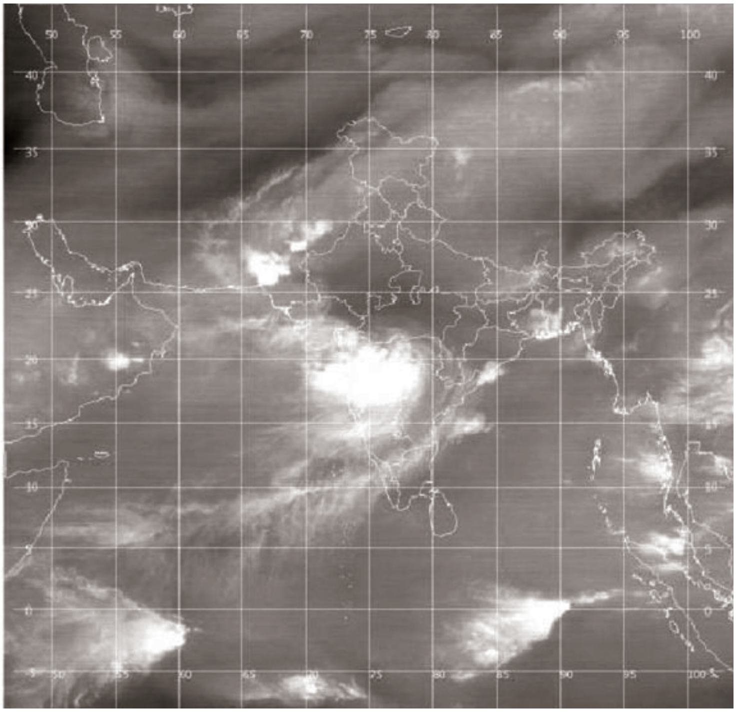


Fig. 2.10(b): Kalpana climate satellite image showing India and its environs in water vapour band.
(*Courtesy:* Indian Meteorology Department)

Fig. 2.11(a): Kalpana climate satellite image showing globe and its environs in colour composite.

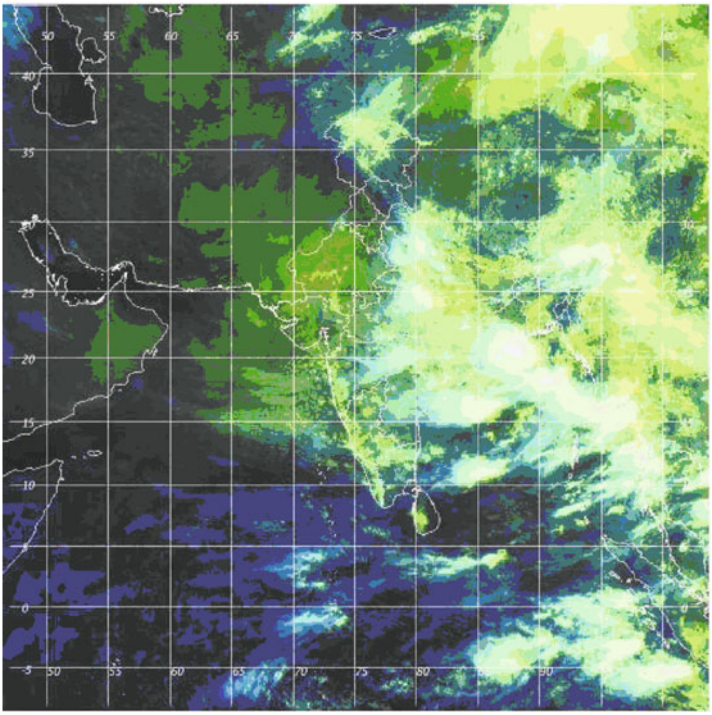


Fig. 2.11(b): Kalpana climate satellite image showing India and its environs in colour composite.
(*Courtesy:* Indian Meteorology Department)

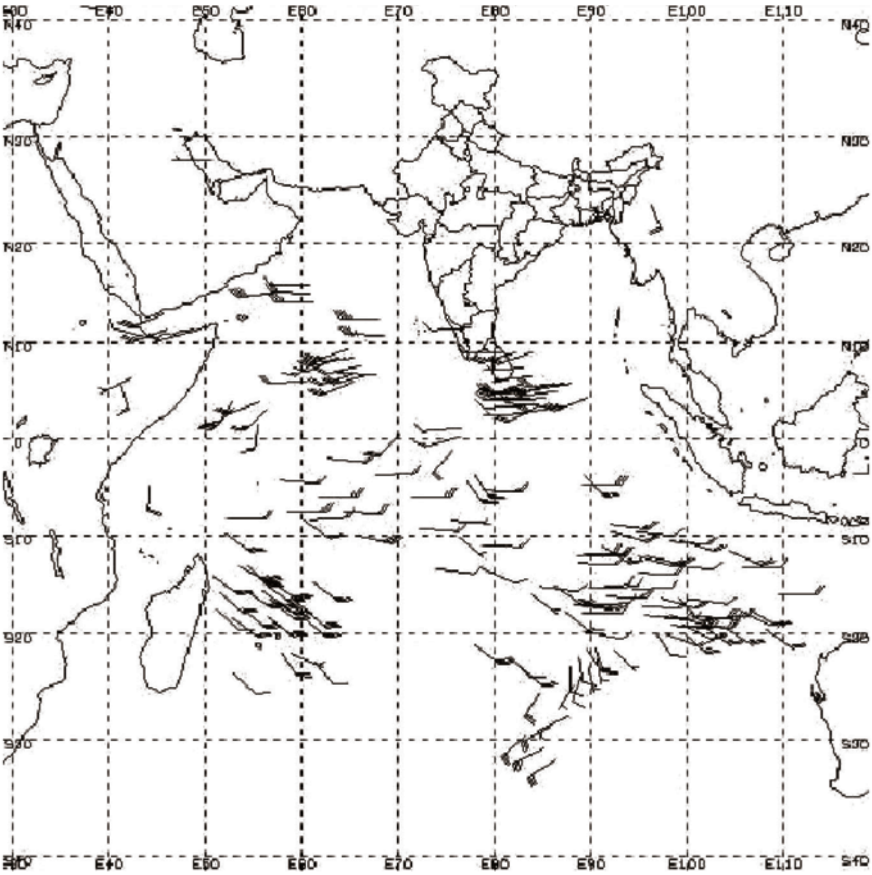


Fig. 2.12: Cloud motion vector (CMV).
(*Courtesy:* Indian Meteorology Department)

darker the pixel in IR images. Clouds which are usually colder than the surface appear white whereas warmer ground or ocean surface appears darker than clouds as in visible image. Water vapour imagery is centered at 6.7 μm and the radiation comes from the middle levels of the troposphere. In the brighter areas, the satellite measures less radiance than in the dark area. Lesser radiance means either that the atmosphere is colder at the same level as in the dark area or that there is more water vapour present in the bright area so that the satellite senses a higher and therefore colder level. The relative humidity is likely to be higher in bright areas than in dark areas. Bright and dark areas also indicate rising and sinking motions respectively. A summary of the cloud identification parameters from satellite visible images is shown in Table 2.1.

Table 2.1: Cloud characteristics portrayed by satellite visible images

Cloud type	*Size*	*Shape*	*Shadow*	*Tone*	*Texture*
Cirriform	Large sheets or bands, hundreds of km long, tens of km wide	Banded, streaky or amorphous with indistinct edges	May cast linear shadows especially on underlying cloud	Light grey to white, sometimes translucent	Uniform or fibrous
Stratiform	Variable from small to very large	Variable, banded amorphous or conforms to topography	Rarely discernible except along fronts	White or grey depending on sun angle and cloud thickness	Uniform or very uniform
Strato-cumuliform	Bands up to thousands of km long; bands or sheets with cells 3-15 km across	Streets, bands or patches with well-defined margins	May show striations along the wind	Often grey over land, white over oceans, due to contrast in reflectivity	Often irregular with open or cellular variations
Cumuliform	From lower limit of photo-resolution to cloud groups, 5-15 km across	Linear streets, regular cells, or chaotic appearance	Towering clouds may cast shadows down sun side	Variable from broken dark grey to white depending mainly on degrees of development	Non-uniform alternating patterns of white, grey and dark grey
Cumulonimbus	Individual clouds tens of km across. Patches up to hundreds of km in diameter through merging of anvils	Nearly circular and well-defined or distorted with one clear edge and one diffuse	Usually present where clouds are well-developed	Characteristically very white	Uniform though cirrus anvil extensions are often quite diffuse beyond main cells.

Source: Barret and Curtis, 1982.

Rainfall Estimation

The advantage of remote sensing systems for weather studies is: (1) High resolution in time and space can be achieved; (2) Spectrum of turbulence and momentum of flux can be measured directly; (3) Integration of given parameter along a line or over an area or through a volume is readily obtained; (4) Scanning of atmosphere in 2 or 3 dimensions is possible; and 5. Sensor is in remote place (Barret and Curtis, 1982). Table 2.2 summarizes the instrumentation that are used in the orbital satellite based rainfall analysis. Regional and international meteorological bureaus rely on the analysis and interpretation of cloud images in both the visible and IR regions. It is generally accepted that the cloud type classification from images is easier in the visible than the IR. However, IR images are advantageous in that they are available for night as well as day, and because of their contents relating to target emission rather than reflections is physically more meaningful revealing the temperatures of radiating surfaces. Where cloud is absent, land and sea surface temperatures can be evaluated; where cloud is present evaluations can be made of the heights of cloud tops above the ground. An idealized schematic of the Meteosat imagery one-dimensional histogram analysis concept and two-dimensional histogram for visible and IR radiance observed by Meteosat is shown in (colour composite) Fig. 2.13. The cloud analysis is used in the preparation of neph-analysis (cloud chart). It describes the cloud

Table 2.2: Instrumentation on-board satellite for cloud identification

Instrument	*Channels micrometer*	*Resolution (km)*	*Swath width (km)*	*Instrumental observations*	*Climate parameter*
AVHRR/3	0.58-0.68 μm 0.725-1.0 1.53-1.73 3.55-3.93 10.3-11.3 11.5-12.5	1	3000	Visible and IR image	Sea surface temperature, Snow cover, albedo, clouds, vegetation cover, ice sheets
TOVS HIRS	20 channels	30	1000	Multi-spectral, IR radiation	Temperature and humidity profiles
SSU	3 channels 668 cm^{-1}	147	1450	Selective absorption of CO_2	Stratosphere temperature profiles
MSU	4 channels 5.5 mm	100	1700	Passive microwave radiance	Temperature profiles
ERBSI	2.50 0.2-0.5	100 87	3000	Visible and IR wide field and scanner	Earth radiation budget
SBUV	12 channels 0.255-0.344	165	Nadir only	Ultraviolet backscatter	Ozone profile, total ozone

Fig. 2.13: Metcosat image showing the cloud pattern over Africa and adjoining areas.
(*Courtesy:* Indian Meteorology Department)

type, the degrees of cloud cover, indication of the structure of the cloud fields, cyclone vertex (interpreted) and jet streams in addition to boundary lines for ice and snow as well as clouds. Climatalogist with sufficient knowledge of the ground information and cloud pattern quantifies the amount of rainfall and its spatial distribution and also the movement of cyclone storms.

The mapping of rainfall (rain-rate and distribution) using satellite image is carried by mapping boundaries of areas likely to be affected by rain, mapping rainfall totals accumulated through unit period of time, assessing intense rainfall events, assessing the climatology of rainfall distribution and forecasting of rainfall. They relate indirectly to rainfall as measured on the ground. *Cloud indexing* method is an extension of classical synoptic meteorology. Rainfall climatology method offers limited support of general crop information services in NOAA. It brings out the relationship between climatologically average rainfall and the long-term average contribution made to it by synoptic weather systems. Life-history method assumes that significant precipitation falls from convective clouds that can be distinguished by images. The rainfall is estimated from cloud performance and the life cycle. Bi-spectral method analyses the visible and infrared image to map the extent and distribution of precipitation with reference to ground data. It assumes that heaviest precipitation falls from clouds that are bright and cold.

Passive microwave methods use radiometer data (19.35 and 37.9 GHz) NIMBUS satellites to predict rainfall over oceans. Rainfall maps based on both conventional and satellite are more realistic in spatial detail than maps based on gauge data alone. Clouds with a cloud-top temperature of less than a threshold value of c-40°C are likely to be rain bearing rather than those with high cloud-top temperatures in tropical areas. The threshold temperature associated with rain-bearing clouds and the quantity of rain they deposit vary temporally and spatially. Thresholds of –50°C in summer and –60°C in the winter for areas north or of –40°C all year round for regions between West Africa and Sahara deserts were established by Tropical Applications in Meteorology of Satellite and other (TAMSAT) program of FAO. Global Precipitation Climatology Project has aided Precipitation Inter comparison and Algorithm Inter comparison projects towards global satellite precipitation monitoring. Rainfall estimation from passive microwave satellite data promises to become the single-most important method for climatological purposes over most of the global surface in the near future. Further they found that the rainfall estimates are lower than the observed ones, in tropical regions.

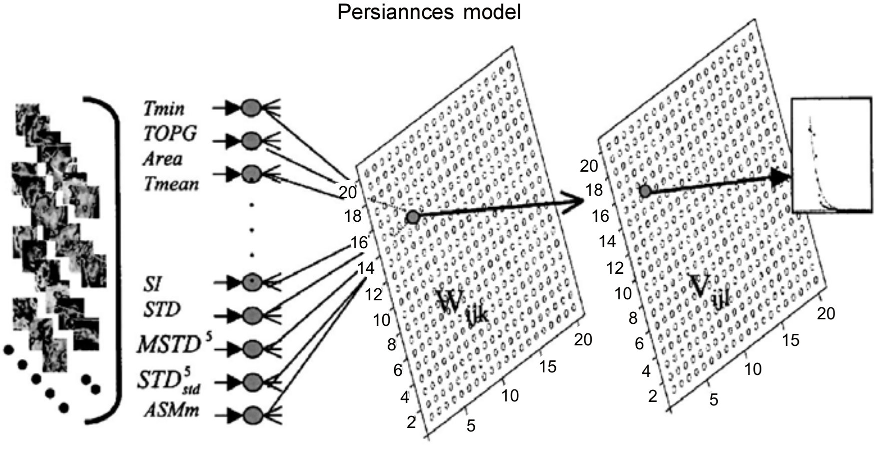
Information retrieval from optical sensor procedures mainly focus on the tropics where precipitation is generally linked with deep convective clouds that can be easily identified in the infrared and/or water vapour channels (Levizzani et al., 2001; Levizzani, 2003), microwave sensors aboard of polar orbiting satellites (low earth orbit, LEO) can principally be used to delineate stratiform raining cloud regions with homogenous cloud-top temperature spatial distributions.

A new technique for the identification of precipitating clouds has been presented that delineates raining from non-raining cloud regions by means of the cloud effective droplet radius and the corresponding cloud optical thickness. The delineation rely on the principle that precipitating clouds must have large enough droplets and a large enough vertical extent to enable sufficient droplet growth and prevent rain droplets from evaporation beneath the cloud base, which in turn has an influence on the required droplet size again. The function for the computation of an auto-adaptive threshold value of the effective radius with respect to the optical thickness is based on a comparison between the rainfall area detected by ground-based radar and corresponding cloud property distributions that have been retrieved using the fast computing SACURA technique. The retrievals were made using satellite measurements of the top-of-atmosphere reflectance at wavelengths 0.66 and 1.6 μm. Cloud-patch-based approaches estimate rainfall based on the cloud coverage under a specified temperature threshold (such as 253 K). The Griffith–Woodley Technique (Griffith et al., 1978; Woodley et al., 1980) tracked a cloud through its lifetime and found threshold. The total rain volume of the cloud patch is determined based on the ratios of satellite cloud area to its maximum coverage. The Convective-Stratiform Technique (Adler and Negri, 1988) is another example of the cloud-patch-based approach. It screens convective cells based on the local minimum of infrared temperature and assigns different rainfall amounts to convective and stratiform components separately. Pixel rain rates are proportionally distributed starting from the coldest pixel to higher-temperature pixels. Xu et al. (1999a) approach determines different temperature thresholds by separating the rain/no-rain pixels in a cloud patch using SSM/I microwave rainfall estimates.

With respect to the use of information, both pixel and local-texture-based approaches only utilize limited attributes of the cloud patches. Rain rates retrieved from these methods tend to be non-unique and may be insufficient to identify the relationships between cloud types and surface rain rates. Cloud-patch-based approaches, on the other hand, attempt to include more information from the cloud images and are likely to provide a more reliable rainfall retrieval system than do the pixel-based approaches. Therefore, successful characterization of cloud patches can be one step toward better estimation of rainfall. However, developing a desirable cloud-patch-based algorithm depends on many factors, including: (1) How effectively the cloud image may be separated into distinct cloud systems or cells; (2) How our knowledge of the cloud systems may be converted into a set of measurable numerical feature vectors, in terms of patch temperature, size, and texture; (3) How these feature vectors may be effectively clustered into a set of separable cloud-patch "classes" or "groups"; and (4) How the cloud-patch groups are associated with the rainfall distributions under the cloud coverage.

The PERSIANN CCS model estimates the rainfall using information from satellite data. Its structural and functional (Fig. 2.14) improvements are: (1) A cloud segmentation procedure that is designed to preprocess IR imagery

Persiannces model



(a) Cloud Segmentation (b) Feature Extraction (c) Cloud Classification (d) Rainfall Mapping

Fig. 2.14: Estimation of rainfall using satellite data and rain gauge information.

into a large number of separated cloud patches through an incremental temperature threshold algorithm; (2) A feature extraction scheme that retrieves both local pixel temperature textures and regional cloud-patch features instead of only local pixel features as in PERSIANN; (3) A cloud classification algorithm (SOFM) that clusters cloud patches into 400 (20 × 20 matrix) groups, based on the cloud-patch features extracted from 230-, 235-, and 253-K temperature levels, respectively; and (4) A cloud-rainfall fitting scheme that calibrates different *Tb–R* functions for each classified cloud cluster instead of a single mapping function in PERSIANN. Coldness features of cloud patch – (1) Minimum temperature of a cloud patch (*T* min); (2) Mean temperature of a cloud patch (*T* mean); Geometric features: (3) Cloud-patch area (AREA); (4) Cloud-patch shape index (SI); Texture features (referring to the brightness temperature texture): (5) Std dev of cloud-patch temperature (STD); (6) Mean value of local standard deviation of cloud temperature (MSTD5); (7) Std dev of local std dev of cloud *Tb* (STD5) std; (8) Gradient of cloud-top brightness temperature (TOPG); and (9) Gray-image texture (maximum angular second moment) are extracted from the cloud patches and used in the rainfall estimation.

Visible and Infra Red data-based techniques have led to the development of cloud indexing approach, thresholding approach and life cycle approach in rainfall estimation (Liu Quanwei, 1996). *Cloud indexing techniques* identifies different types of rain clouds and estimates the rainfall from the number and the duration of clouds or their area. Satellite cloud images are ascribed indices relating to cloud cover and the probability and intensity of associated rain. *Earthsat method* provides input to crop yield models and commodity forecasting systems. It uses a regression approach to estimate 6-hour precipitation from temperature and empirical information for the major crop growing regions of the world. *Bristol method* uses an empirical relationship between satellite determined cloud indices, climatic indices dependent on the mean monthly rainfall and 12-hour rainfall totals. It has shown to be most flexible and yielded the first results in support of operational monitoring program. *Thresholding techniques* consider that all clouds with low upper-surface temperature are likely to be rain clouds. It is based on cloud-top brightness and cloud-top temperatures. Cloud brightness technique assumes that the precipitating clouds are often brighter than others. Hence, automatic brightness thresholding can be used to map rainfall from visible images of satellite and calibrated using rain gauge and/or radar observations. It uses daytime visible and thermal IR image pairs to establish rain or no-rain thresholds. Cloud temperature from thermal IR imagery is analyzed to identify potential rain clouds.

Life-cycle methods consider the rates of changes in individual convective colours or in clusters of convective clouds. It is designed to provide rain estimates from any type of convectional clouds by taking into objective consideration of the growth or dissipation of individual clouds with time. It recognizes that convective clouds exhibit different rainfall intensities during their growth and dissipation cycle. *Woodley-Griffith technique* (Griffith et al., 1978) uses an empirically derived relationship between calibrated ground positioned radar echoes and geostationary satellite imagery of cloud areas. A time-cycle relationship between the radar echo area and the cloud area is developed for discrete time intervals during the lifetime of the cloud. Scofield (1986) has developed a series of seven convective and five extratropical cloud categories that can be used to help meteorologists improve their estimates of heavy precipitation across a range of different weather situation. *Looping technique* graphically displays the life cycle of synoptic and mesoscale meteorological features on a successive satellite imagery. An image loop is created by rapidly displaying a series of images to create a sense of movement (a time series of images). It is useful for quantifying the movement of features such as hurricanes, frontal systems or large thunderstorm complexes; identify features that are moving; and identify features that have unique spectral signature.

Microwave radiation with wavelengths of the order of 1 mm to 5 cm results in strong interaction between the raindrops and the radiation. Electrically Scanning Microwave Radiometers (ESMR-5 19.35 GHZ) measures the naturally emitted microwave radiation from the surface of earth and water content of the atmosphere. It provides maps of instantaneous precipitation intensities. Grody et al. (1984) developed an algorithm based on the difference in measured brightness and temperature at two frequencies. The relationship between emissions and frequency decreases for most surfaces but increases for dry snow, old sea ice and in the presence of scattering caused by raindrops and it is found to enhance the precipitation effects and minimize the surface emissivity. Passive microwave data is less frequently available over space and time. So, combination of visible, infrared and passive microwave data was developed by Barrett et al. (1988). It is found that they could locate the leading and trailing edges of rain areas, confirm the extent of rain areas, if no visible/IR data were available, local heavy-rain areas where cumulonimbus cells are located within stratiform clouds and located areas of rain that could not be normally identified. Based on the success of rainfall estimation, Tropical Rainfall Measurement Mission (TRMM) with both passive and active sensors onboard satellite has been formulated (Simpson and Theon, 1991). It contains multichannel dual polarized passive microwave radiometer with 14 GHZ rain radar and six-channel visible/IR instruments. The orbit elevation would be at 350 km having swath width of 220 km for radar and 600 km for others, to obtain high resolution of 24 km, 4 km and 2 km at nadir for passive microwave 19 channels, the radar and visible/IR respectively.

Application

The main advantage of the geostationary over polar satellites is the high temporal resolution of their data. The disadvantage is their limited spatial resolution, which is a consequence of their distance from earth. Also distortion at high latitudes limits useful information to the belt between 70° N and 70° S. Information on cloud thickness and height can be deduced from satellite photographs. In visible region, reflected sunlight from the cloud's upper surface has brighter shades due to its higher albedo (reflectivity). It is difficult to distinguish between the high, moderate and low clouds. In Infrared region, warm objects radiate more energy than cold objects, and high temperature regions can be artificially made to appear darker on infrared images. Tops of low clouds are warmer than those of high clouds i.e. warm low clouds are dark and cold high clouds light. The elongated bands of clouds mark the position of an approaching weather front. Cloud image enhancement: image processing like that of land cover pattern on the surface are used in classification. In regions where there are no clouds, it is difficult to observe the movement of the air. Water vapour sensors profile the distribution of atmospheric water vapour in the middle and upper troposphere. Successive images would show swirling patterns of moisture clearly, wet and dry regions as well as middle tropospheric swirling wind patterns and jet streams. The thermal or infrared images recorded by sensors called scanning radiometers enable a trained analyst to determine cloud heights and types, to calculate land and surface water temperatures, and to locate ocean surface features. These infrared pictures depict ocean eddies or vortices and map currents such as the Gulf Stream which are valuable to the shipping industry. *Solar Radiation:* Daily surface solar exposure is estimated using a physical model of radiative transfer within the atmosphere, visible spectrum satellite data and other ancillary data. This model is based on a two-band developed for data from GMS-5. *Cloud and Water Vapour Motion Vector Winds:* It generates, on an hourly basis, high spatial and temporal resolution cloud and water vapour motion vectors using geostationary satellite data. The data is assimilated into the Numerical Weather Prediction (NWP) models operationally in real time. Impact has also been made using these winds in local NWP models for tropical cyclone forecasting. *Low Cloud/Fog Detection:* Algorithms using AVHRR Channels 3 and 4 in particular are used to detect fog or low cloud especially at night or before sunrise because contrast enhanced visible imagery is only useable when scenes are sunlight illuminated. Fog and low clouds are important in aviation weather services.

Tropical Rainfall Measuring Mission (TRMM) satellite obtains sea surface temperatures with a microwave scanner that penetrates into clouds and atmospheric particles. Satellites measure radiation from the earth's surface and atmosphere giving us information about the earth-atmosphere energy balance. The Infrared radiation measurements obtained by an atmospheric sounder are transformed into vertical profiles of temperature and moisture and used in forecast models. ENVISAT altimeter data from the European Space Agency (ESA) and Quik SCAT scatterometer data from NOAA NESDIS via the GTS network (or internet) is used to supplement the conventional data with surface wind speeds for input into the global and regional Numerical Weather Prediction (NWP) models.

2.7 Precipitation

Precipitation begins forming when warm, moist air rises. As the air cools, water vapour begins to condense on condensation nuclei, forming clouds. After the water droplets grow large enough, two processes can occur to form precipitation. *Coalescence* occurs when water droplets fuse to create larger water droplets, or when water droplets freeze onto an ice crystal. Air resistance typically causes the water droplets in a cloud to remain stationary. When air turbulence occurs, water droplets collide, producing larger droplets. As these larger water droplets descend, coalescence continues, so that drops become heavy enough to overcome air resistance and fall as rain. Coalescence generally happens most often in clouds above freezing. *Bergeron process* occurs when ice crystals acquire water molecules from nearby super-cooled water droplets. As these ice crystals gain enough mass, they begin to fall. This generally requires more mass than coalescence when occurring between the crystal and neighbouring water droplets. This process is temperature dependent, as super-cooled water droplets only exist in a cloud that is below freezing. In addition, because of the great temperature difference between cloud and ground level, these ice crystals may melt as they fall and become rain. Cloud droplets are very small, much too small to fall as rain. The smaller the cloud droplet, the greater its curvature and the more likely it will evaporate. Cloud droplets form on cloud condensation nuclei. Hydroscopic nuclei such as salt allow condensation to begin when the relative humidity is less than 100 percent. Cloud droplets in above freezing air can grow larger as faster-falling, bigger droplets collide and coalesce with smaller droplets in their path. In the ice-crystal (Bergeron) process of rain formation, both ice crystals and liquid cloud droplets must coexist at below freezing temperatures. The difference in saturation vapour pressure between liquid and ice causes water vapour to diffuse from the liquid droplets (which shrink) toward the ice crystals (which grow). Most of the rain that falls over middle latitudes results from melted snow formed from ice-crystal (Bergeron) process. Cloud seeding with silver iodide can only be effective in coaxing precipitation from clouds if the cloud is super cooled and the proper ratio of cloud droplets to ice crystals exists.

Falling raindrops and snowflakes may be altered by atmospheric conditions encountered beneath the cloud and transformed into other forms of precipitation that can profoundly influence our environment. *Rain* is a falling drop of liquid water having a diameter equal to or greater than 0.5 mm. Fine uniform drop of water whose diameter is less than 0.5 mm is called as *drizzle*. The rain falling from a cloud never reaches the surface because of the low humidity that causes rapid evaporation. The drops become smaller and their rate of fall decreases and appears to hang in the air as a rain streamer. These evaporating streaks of precipitation are called *virga*. Raindrops may also fall from a cloud and not reach the ground, if they encounter rapidly rising air. Large raindrops have a terminal velocity of about 9 m/sec. If the updraft weakens or changes direction and becomes a downdraft, the suspended drops will fall to the ground as sudden rain *shower*. Showers falling from cumuliform clouds are usually brief and sporadic as cloud moves overhead and then drift on by. If the shower is excessively heavy, it is termed as cloudburst. Continuous rain falls from layers of cloud that covers a large area and has smaller vertical air currents. It is important to know the interval of time over which rain falls. The intensity of rain is the amount that falls in a given period – light (0.01 to 0.10 inches/hr); moderate (0.11 to 0.30 inches/hr) and heavy (> 0.30 inches/hr).

Spot Measurement and Observation

The standard way of measuring rainfall or snowfall is the standard rain gauge, which can be found in 4-inch/100 mm plastic and 8-inch/200 mm metal varieties. The inner cylinder is filled by 25 mm/one inch of rain, with overflow flowing into the outer cylinder. Plastic gauges will have markings on the inner cylinder down to 0.25 mm/0.01" resolution, while metal gauges will require use of a stick designed with the appropriate 0.25 mm/0.01" markings. After the inner cylinder is filled, the amount inside it is discarded, then filled with the remaining rainfall in the outer cylinder until all the fluid in the outer cylinder is gone, adding to the overall total until the outer cylinder is empty. These gauges are winterized by removing the funnel and inner cylinder and allowing the snow/freezing rain to collect inside the outer cylinder. Once the snowfall/ice is finished accumulating, or as you approach 300 mm/12", one can either bring it inside to melt, or use luke warm water to fill the inner cylinder with in order to melt the frozen precipitation in the outer cylinder, keeping track of the warm fluid added, which is subsequently subtracted from the overall total once all the ice/snow is melted. Other types of gauges include the popular wedge gauge (the cheapest rain gauge and most fragile), the tipping bucket rain gauge (Fig. 2.15), and the weighing rain gauge. The wedge and tipping bucket gauges will have problems with snow. Attempts to compensate for snow/ice by warming the tipping bucket

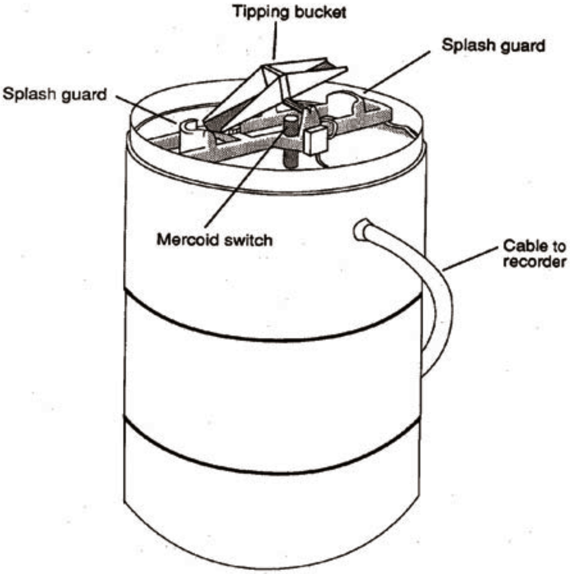


Fig. 2.15: Tipping bucket rain gauge.

meet with limited success, since snow may sublimate if the gauge is kept much above freezing. Weighing gauges with antifreeze should do fine with snow, but again, the funnel needs to be removed before the event begins. For those looking to measure rainfall most inexpensively, a can that is cylindrical with straight sides will act as a rain gauge if left out in the open, but its accuracy will depend on what ruler you use to measure the rain. Stand alone total weather stations measure and record the weather related parameters of a place using data loggers and recorders using uninterrupted power packs. Successful efforts are made by people in transmitting to the nearest data gathering centre using wireless networks.

Various networks exist across the United States and elsewhere where the rainfall measurements can be uploaded through the internet, such as CoCoRAHS or GLOBE. An important use of precipitation data is for forecasting of river flows and river water quality using hydrological transport models such as SWMM, SHE or the DSSAM model. Much of our knowledge concerning precipitation processes has been inferred from observations and by the use of instruments which measure precipitation amount and intensity. Simplest and oldest method of assessing precipitation amount is by the use of gauges, imitated by the milk bottle and kitchen funnel. This technique still provides the bulk of the world's daily or monthly precipitation statistics. Precise and accurate rainfall measurement is possible with the minimum of skill of the observer. The precipitation collected in such a gauge is measured either *volumetrically* or in terms of *precipitation depth*. Calibration of the collecting vessel exactly equals the collecting diameter of the funnel. The problem of this measurement is more complex if solid forms of precipitation are to be measured or if evaporation losses are to be taken into account. Conventionally this sort of manual measurement is made at monthly, weekly or daily intervals (generally at 9.00 local standard time). Sources of error in this method of measurement are: design of instrument and also observer; site and location errors (intrusion into and interference with the surrounding environment, turbulence effect due to surrounding trees and buildings, splash-in from the surrounding land surface) and in assessing how representative gauge catch is statistically of the true precipitation. The *simple depth gauge* uses the funnel and bottle pattern where water is collected by a funnel of known diameter and stored for later measurement in a collecting bottle beneath. Water is transferred from the collecting bottle to measuring cylinder, so that estimates of rainfall may be made to the nearest 0.1 mm. *Pluviographs, the tipping bucket recorder*, measures the time of rainfall occurrence and intensity, mostly in the form of the rate of accumulation rainfall over time on a chart. It is prone to freezing damage which can be relatively costly to repair. *Natural siphon recorder* mechanism is used to empty the collecting vessel once it is full. A horizontal trace on the chart indicates no change in the level of water in the chamber and thus no rainfall. During periods of rainfall, the slope of the trace indicates the rainfall intensity. These are mechanical rather than electrical or electronic, since they date from the 'clockwork and ink' phase of instrumentation in meteorology. In tilting siphon recorder rain gauge the mechanism is causing the chamber to tilt in order to siphon (time taken 10 to 20 sec) its contents (generally 5 mm rainfall). This mechanism takes some time to adjust so that it operates effectively.

Areal Representation and Network Design

Analysis of precipitation variation through time and over space yields relationship between short-term precipitation intensities and long-term totals. They exhibit a site or area-dependency that could be used in understanding the nature and magnitude of the meteorological processes producing the precipitation. Precipitation is highly variable over time and space scale. While considering more than one rain gauges in run-off analysis, the distance between the stations are considered. It is assumed that the influence of the station will be 50% of the horizontal distance. Based on the recorded rainfall amount, isohyetal (line connecting equal rainfall amount) map (Fig. 2.16) showing the distribution is prepared on national or watershed level. Hence, it is important to identify *Precipitation climatology* of a location incorporating seasonal and daily precipitation occurrence that highlights the precipitation-producing processes of area. This process is governed by global geographical variation, marked seasonal and monthly variations. This would ascertain the

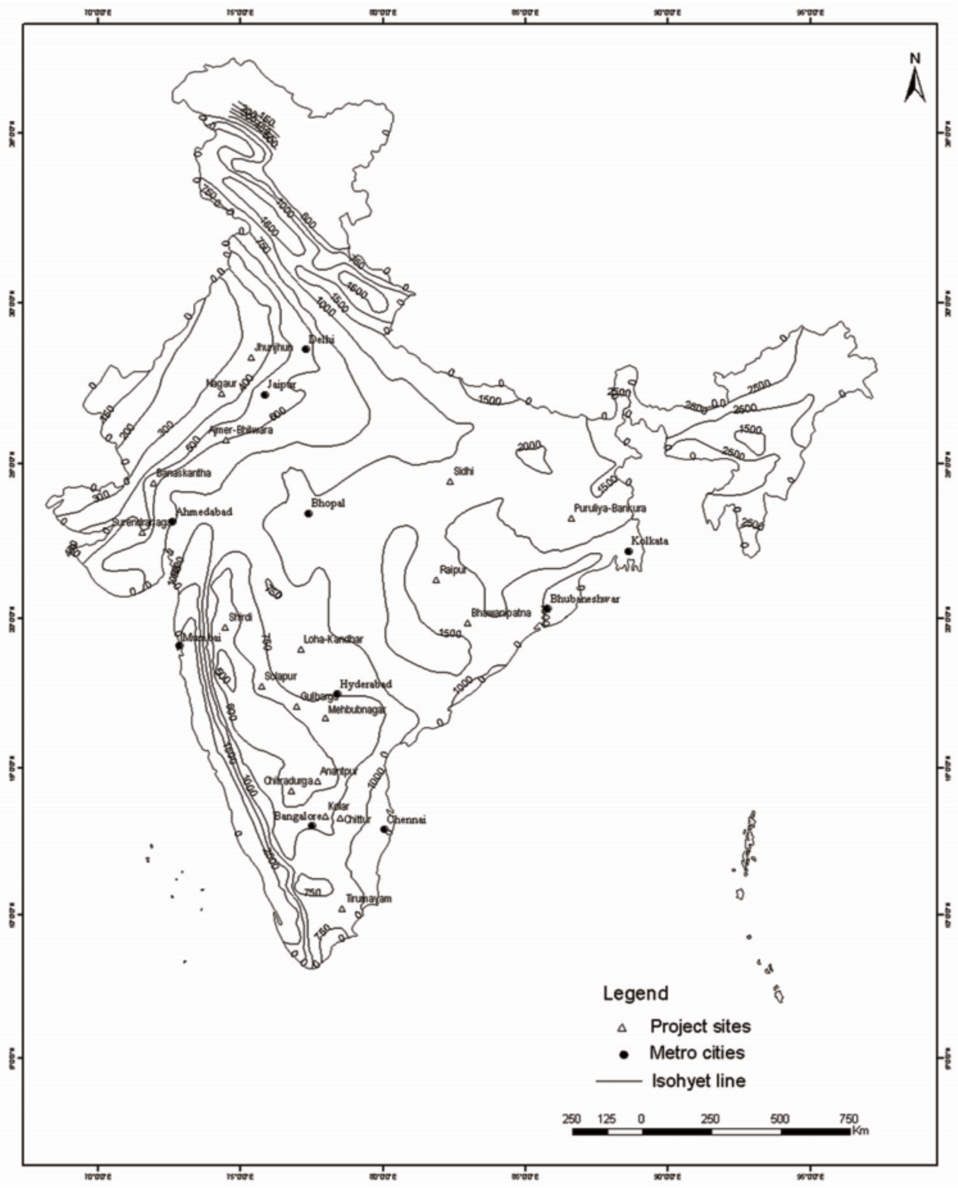
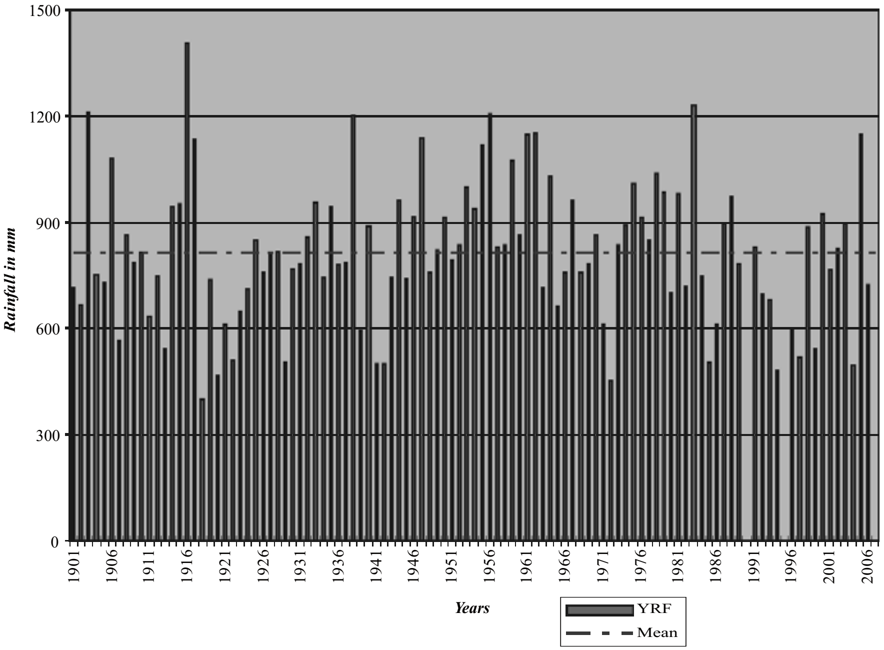


Fig. 2.16: Annual rainfall (isohyet) of India.
Source: Central Ground Water Board, 1989

general nature of precipitation in terms of normal expectations in amount, intensity and distribution through the year or day in isolating any long-term trends or oscillations through time. *System signature* highlights the character of precipitation amount (intensity) through time within a typical or even particular precipitation event – temporal frontal depression or a small rain shower.

2.8 Precipitation Climatology

Annual variation describes the year-to-year variation in total amount. Such trends have an impact over time spans of the order of decades and arguably due to the impact of man's global industrial activities (greenhouse effect), global warming, local causes, etc. Continued changes in annual precipitation receipt beyond decadal periods indicate pronounced regional climate change. *Intra-annual variation* describes the seasonal and monthly variations in precipitation in year and departures from the means in individual years. Changes in regional atmospheric circulation govern the process by which precipitation produced is reflected by the short-term character of precipitation events in time and space. Annual rainfall analysis (Fig. 2.17) indicates the trend of rainfall in an area (coarse information) while monthly rainfall (Fig. 2.18) indicates the distribution of rain during the crop growing season (moderate). Daily or weekly rainfall analysis (Fig. 2.19) indicates the support from rainfall between the crop watering periods of the previous years. It is



Mean for : Total Years - 814.07 1901-1910 : 816.94 1911-20 : 795.81 1921-30 : 698.72 1931-40 : 852.93 1941-50 : 799.25 1951-60 : 948.17 1961-70 : 882.31 1971-80 : 828.14 1981-90 : 826.96 1991-2000 : 683.58 2001-07 : 824.18

Fig. 2.17: Annual rainfall analysis of rain gauge station with means for 10 years.
Source: Indian Meteorological Department/Revenue Department, Maharashtra

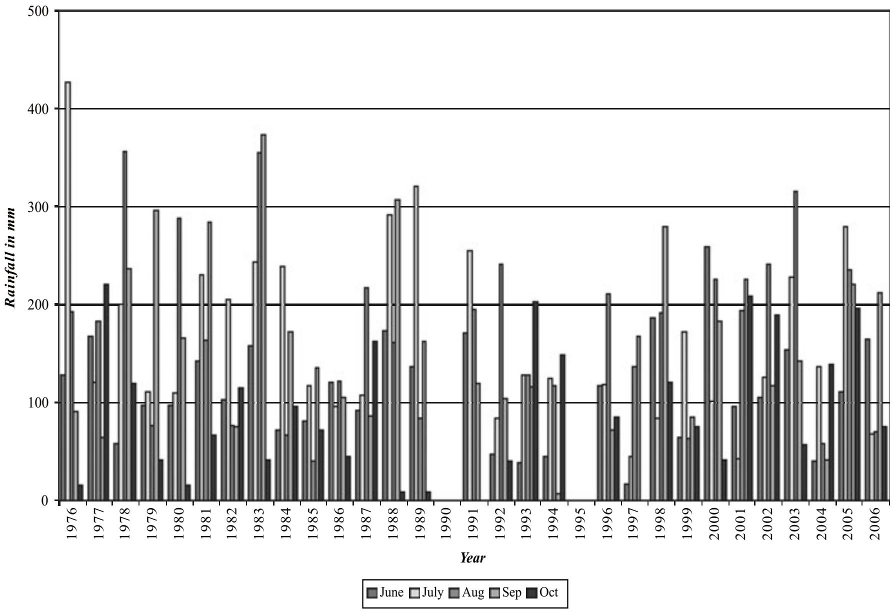


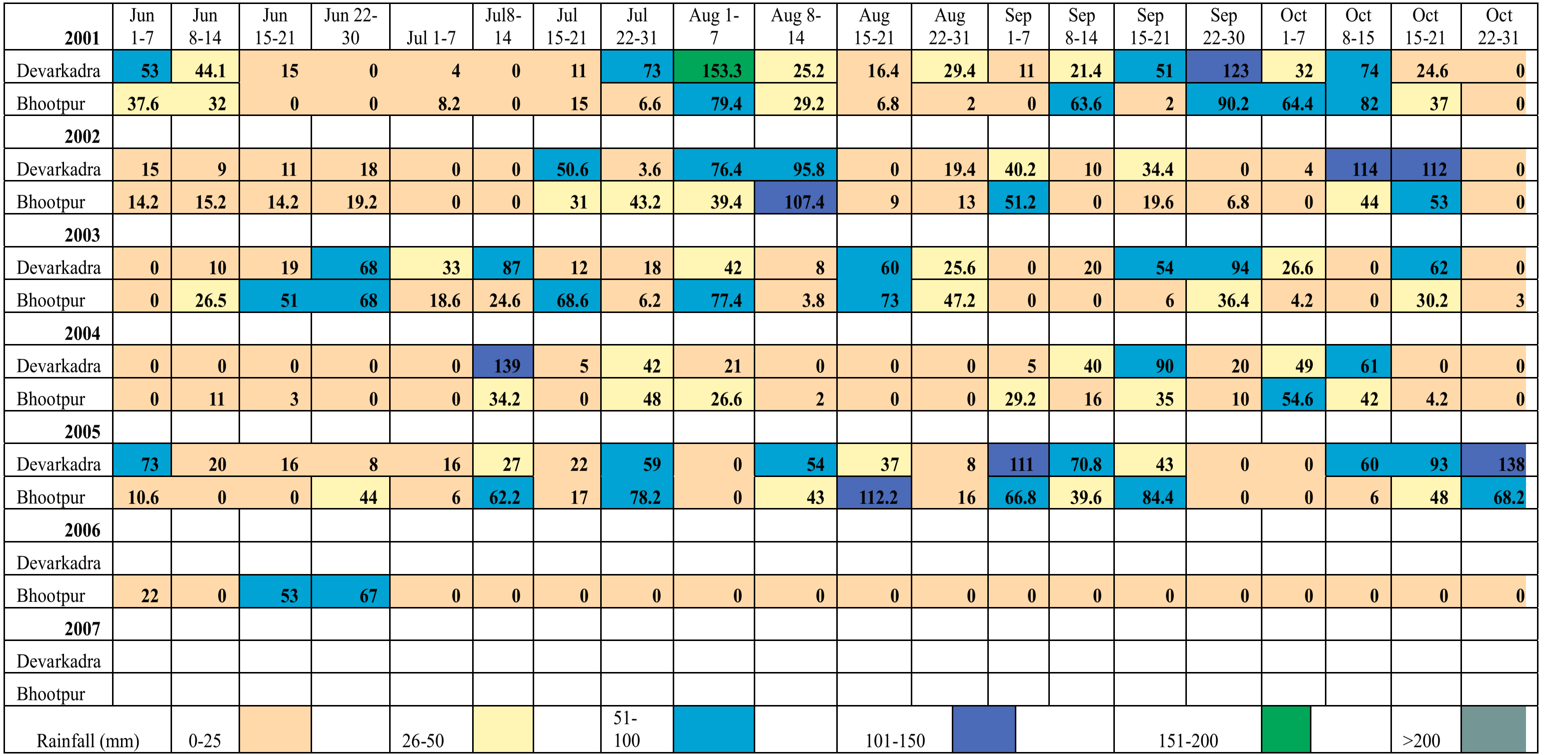
Fig. 2.18: Monthly rainfall analysis of rain gauge station.
Source: Indian Meteorological Department/Revenue Department, Maharashtra

also closely tied to seasonal circulation and insolation changes associated with passage of the zenithal sun between two tropics in June and December. Quantitative indices that indicate seasonal variability are estimated by: (1) statistical approach describing the arrival and departure of the rain, and (2) empirical approach based on monthly rainfalls, expressed as proportions of the annual mean to derive an overall index of rainfall seasonality. Seasonality index (SI) is calculated as

$$\mathrm{SI} = 1/R \sum_{n=1}^{n=12} | \overline{X}_{\mathrm{n}} - \overline{R}/12 |$$

where R is the mean or total annual rainfall and X_{n} is the mean or actual monthly rainfall for month n.

In regions where rainfall is strongly seasonal, the time of onset and end of the rainy season or seasons will be of considerable importance, since it determines the extent of the growing season. Benoit (1977) has used the date on which accumulated rainfall exceeds and remains greater than half the potential evapotranspiration for the remainder of the growing season provided that no dry spell longer than five days occurs immediately after this date. Daily variation shows a considerable variation from zero to more than 1500 mm. Daily precipitation magnitude are "rain days" on which at least 0.25



2001	Jun 1-7	Jun 8-14	Jun 15-21	Jun 22-30	Jul 1-7	Jul8-14	Jul 15-21	Jul 22-31	Aug 1-7	Aug 8-14	Aug 15-21	Aug 22-31	Sep 1-7	Sep 8-14	Sep 15-21	Sep 22-30	Oct 1-7	Oct 8-15	Oct 15-21	Oct 22-31
Devarkadra	53	44.1	15	0	4	0	11	73	153.3	25.2	16.4	29.4	11	21.4	51	123	32	74	24.6	0
Bhootpur	37.6	32	0	0	8.2	0	15	6.6	79.4	29.2	6.8	2	0	63.6	2	90.2	64.4	82	37	0
2002																				
Devarkadra	15	9	11	18	0	0	50.6	3.6	76.4	95.8	0	19.4	40.2	10	34.4	0	4	114	112	0
Bhootpur	14.2	15.2	14.2	19.2	0	0	31	43.2	39.4	107.4	9	13	51.2	0	19.6	6.8	0	44	53	0
2003																				
Devarkadra	0	10	19	68	33	87	12	18	42	8	60	25.6	0	20	54	94	26.6	0	62	0
Bhootpur	0	26.5	51	68	18.6	24.6	68.6	6.2	77.4	3.8	73	47.2	0	0	6	36.4	4.2	0	30.2	3
2004																				
Devarkadra	0	0	0	0	0	139	5	42	21	0	0	0	5	40	90	20	49	61	0	0
Bhootpur	0	11	3	0	0	34.2	0	48	26.6	2	0	0	29.2	16	35	10	54.6	42	4.2	0
2005																				
Devarkadra	73	20	16	8	16	27	22	59	0	54	37	8	111	70.8	43	0	0	60	93	138
Bhootpur	10.6	0	0	44	6	62.2	17	78.2	0	43	112.2	16	66.8	39.6	84.4	0	0	6	48	68.2
2006																				
Devarkadra																				
Bhootpur	22	0	53	67	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2007																				
Devarkadra																				
Bhootpur																				

Rainfall (mm) 0-25 🟧 26-50 🟨 51-100 🟦 101-150 🟪 151-200 🟩 >200 ⬜

Fig. 2.19: Weekly rainfall analysis of rain gauge station.

mm has fallen or wet days when more than 1.0 mm occurs (UK Meteorological Office). In most of the tropical areas, rainfall occurs as a result of convectional processes or as the result of mobile synoptic-scale features such as tropical depressions or cyclones. The magnitude of precipitation developed during a day depends on the degree of atmospheric instability and moisture supply, so that rainfalls are highly variable from day to day in tropical areas. In non-tropical areas, large scale atmospheric circulation and air masses govern the convection and by highly mobile temperature depression make for an even lesser predictable daily precipitation climatology.

Formation of monsoon clouds and their movement determines the rainfall in tropical monsoon areas like India. Any delay in their advancement upsets the agriculture preparations. On-set and advancement of South West monsoon over India is shown in Fig. 2.20. This is considered as one among the indicators of drought. In temperate regions during the summer months, convectional processes predominate and may produce a distinct diurnal variation in precipitation. Atmospheric and insolation conditions promote the establishment of sufficient daytime convection which produces showers and storms. The main deficiency of analyses based on rainfall alone is that plant production is related to the 'use' of water and only indirectly to its 'supply'. Water use may be greater than rainfall in situations where there is depletion of soil water or less than normal rainfall, when there is runoff or infiltration below the root zone. Other deficiencies of simple rainfall analyses are that interception losses are ignored, and all rainfall, irrespective of the season in which it falls or the amount in a particular storm, is erroneously considered to be of equal value. Furthermore these analyses ignore the soil as a storage buffer.

2.9 Rainfall Reliability Wizard

A new computer-based tool, the Rainfall Reliability Wizard, has been developed by Laughlin et al. (2003) for rapid spatial assessments of rainfall reliability. It employs conditional statistical methods to analyze rainfall reliability using over 100 years of gridded monthly rainfall data across Australia. The available functions of the wizard are shown below. The resolution of the grid rainfall data is the major limiting factor of the accuracy of the spatial and temporal analyses provided by the Wizard. The 25 km grids presently available are often too coarse when an analysis is required for a small region with localised orographic rainfall variability (Clark et al., 2000).

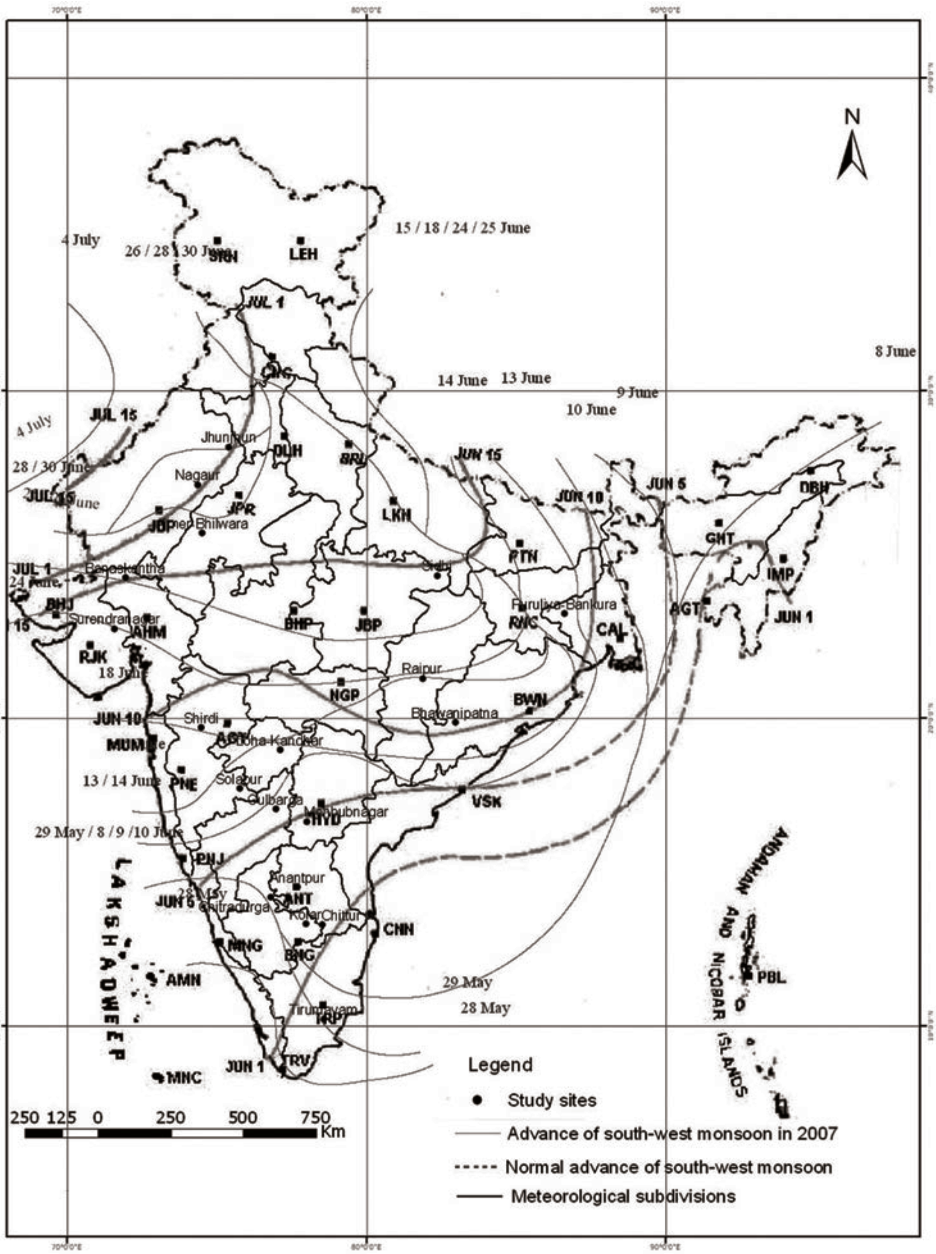


Fig. 2.20: On-set and advancement of south west monsoon over India.
Source: Indian Meteorological Department

Functions of the Rainfall Reliability Wizard (Laughlin et al., 2003)

Function	*Description*
	Historical analysis
1. Mean	User defines a "season", say June to October, and the system generates a map (or grid ASCII for export) showing the approximate mean (average) rainfall in millimetres for that season. The mean is always based on all years of record (currently, nearly 102). Standard calendar seasons can be selected using buttons or any contiguous months up to 12.
2. Percentile	User defines a "season", as well as a percentile, say 25, and the system generates a map showing the approximate rainfall in millimetres corresponding to the 25th percentile on a pixel-by-pixel basis.
3. Inter-season reliability	User defines a "season", say June to October, as well as a target in millimetres for that season, Absolute say 250. System generates a map showing the proportion of years that the target has been exceeded. An answer of 0.4 would imply that in approximately 40 years out of 100, 250 mm is exceeded in June to October.
4. Inter-season reliability	As for 3 but where the target is expressed as a proportion of the (seasonal) mean. The system relative calculates the seasonal mean for each pixel and then the proportion of years the target has been exceeded on a pixel-by-pixel basis.
5. Intra-season reliability	User defines a season and a target in millimetres for each month of the season, say 50 in June, absolute 70 in July and 90 in August. System generates a map showing the approximate proportion of years that the targets have been exceeded in all months. An answer of 0.4, for example, would imply that in approximately 40 years out of 100 the targets (50, 70, 90) have (all) been exceeded.
6. Intra-season reliability	As for 5 but where monthly targets are expressed as proportion of the monthly means. System calculate the proportion of years the targets has been exceeded, again, on a pixel-by-pixel basis.
	Event analysis
7. Event analysis	User defines an event, say June to October 1990 and the system generates a map showing the

(*Contd.*)

(*Contd.*)

	approximate rainfall in mm that fell during the event, in this case June to October 1990.
8. Event analysis percentile	User defines an event, and the system generates a map showing the event's rainfall expressed as Percentile × percentiles, where 1 is the lowest (driest) and 100 the highest (wettest) on record.
9. Multiple events	The system is able to handle single events of up to 5 years, as well as multiple events, say three seasons in a row where targets have been exceeded. In addition, non-contiguous events (e.g. June, July, August, September, October, November) and multiple non-contiguous events are also possible. Absolute and relative (to the mean) options are available within each function.

Hence, it is necessary to identify the climatic conditions such as presence or absence of monsoon and its reliability in terms of rainfall and arrival consistency, rainfall and temperature variation, aridity/humidity conditions, wind conditions etc., in deriving at the meteorological drought. This could be based on the time-series analysis, cloud pattern as portrayed by the satellite (global/regional scale) or ground-based observations and rainfall relationship and rainfall that falls on the ground takes different routes in reaching the surface and sub-surface storage systems. Understanding of the hydrological processes that are used in drought analyses is given in detail in the next chapter.

References

Adler, R.F. and Negri, A.J. (1988). A satellite infrared technique to estimate tropical convective and stratiform rainfall. *J. Applied Meteorology*, **27**, pp. 30-51.

Barrett, E.C., D'Souza, G., Power, C.H. and Kidd, C. (1988). Towards trispectral satellite rainfall monitoring algorithms. Proceeding of Tropical Precipitation Measurements International Symposium, Tokyo, Japan, NASS/NASDA, (eds) Thon, J.S., Fugono, J. and A. Depak, Hampton, pp. 285-292.

Barrett, E.C. and Curtis, M.J. (1992). Satellite rainfall monitoring: An overview. *Remote Sensing Reviews*, **11,** pp. 23-48.

Clark, A.J., Brinkley, T.R., Lamont, B. and Laughlin, G.P. (2000). Exceptional Circumstances: A case study in the application of climate information to decision making. *In:* Proceedings of Cli-manage conference held on 23-25 October 2000. Albury, NSW.

Griffith, C.G., Woodley, W.L., Grube, D.W., Stout, M.J. and Sikdar, D.N. (1978). Rain estimation from geosynchronous satellite imagery – Visible and infrared studies. *Mon. Weather. Rev.*, **106**, pp. 1153-1171.

Grody, N.C. (1984). Precipitation monitoring overland from satellite by microwave radiometry, presented at 1984 International Geoscience and Remote Sensing Symposium (IGARSS'84), Strasbourg, France. ESA SP-215, pp. 417-423.

Laughlin, G.P., Heping Zuo, Walcott, J. and Bugg, A.L. (2003). The rainfall reliability wizard – A new tool to rapidly analyze spatial rainfall reliability with examples. *Environmental Modelling and Software*, **18**, pp. 49-57.

Levizzani, V., Schmetz, J., Lutz, H.J., Kerkmann, J., Alberoni, P.P. and Cervino, M. (2001). Precipitation estimations from geostationary orbit and prospects for Meteosat Second Generation. *Meteorological Applications*, **8**, pp. 23-41.

Levizzani, V. (2003). Satellite rainfall estimations: New perspectives for meteorology and climate from the EURAINSAT project. *Annals of Geophysics*, **46**, pp. 363-372.

Liu Quanwei (1996). The application of remote sensing in rainfall monitoring. Helsinki University of Technology.

Simpson, J. and Theon, J.S. (1991). The Tropical Rainfall Measuring Mission (TRMM) and its role in studies of climate variations. Presented at the 1991 International Geoscience and Remote Sensing Symposium (IGARSS'91), June 3-6, 1991, Espoo, Finland.

Sulochana, Gadgil, Rajeevan, M. and Nanjundiah, R. (2005). Monsoon prediction – Why yet another failure? *Current Science*, **88(9)**, pp. 1389-1400.

Woodley, W.L., Griffith, C.G., Griffin, J.S. and Stroomatt, S.C. (1980). The inference of GATE convective rainfall from SMS-1 imagery. *J. Applied Meteorology*, **19**, pp. 338-408.

Xu, L.X., Gao, X., Sorooshian, S., Arkin, P.A. and Imam, B. (1999a). A microwave infrared threshold technique to improve the GOES precipitation index. *Journal of Applied Meteorology*, **38**, pp. 569-579.

Xu, L.X., Sorooshian, S., Gao, X. and Gupta, H. (1999b). A cloud-patch technique for identification and removal of no-rain clouds from satellite infrared imagery. *Journal of Applied Meteorology*, **38**, pp. 1170-1181.

Further Reading

Ahrens, Donald C. (2003). Meteorology today – An introduction to weather, climate and the environment. Thomson and Brooks/Cole, Australia, pp. 542.

Ann Welch (1973). Pilots' weather – A flying manual. John Murray (Publishers) Ltd, London, pp. 268.

Cagle, M.W. and Halpine, C.G. (1970). A pilot's Meteorology. Van Nostrand Reinhold, New York, pp. 407.

Clausen, B. and Pearson, C.P. (1995). Regional frequency analysis of annual maximum stream flow drought. *Journal of Hydrology*, **137**, pp. 111-130.

Ferraro, R.R., Grody, N.C. and Marks, G.F. (1994). Effects of surface conditions on rain identification using the DMSP-SSM/I. *Remote Sensing Review*, **11**, pp. 195-210.

Graham Sumner (1988). Precipitation – Process and analysis. John Wiley and Sons, New York, pp. 454.

Horn, D.H. (1989). Characteristics and spatial variability of droughts in Idaho. *Journal of Irrigation and Drainage Engineering, ASCE*, **115(1)**, pp. 123.

Kumar, V. and Panu, U. (1997). Predictive assessment of severity of agricultural droughts based on agro-climatic factors. *Journal of The American Water Resources Association*, **33(6)**, pp. 1255-1264.

Kumar, V. and Panu, U. (1997). On application of pattern recognition in drought classification. Annual Conference of CSCE, pp. 71-76.

Lohani, V.K. and Loganathan, G.V. (1997). An early warning system for drought management using Palmer Drought Severity Index. *Nordic Hydrology*, **29(1)**, pp. 21-40.

Oliver, H. (1961). Irrigation and climate. Edward Arnold Limited, London, pp. 250.

Palmer, W.C. (1965). Meteorological drought. Research paper no. 45, US Weather Bureau, Washington DC Feb., pp. 58.

Pant, P.S. (1981). Medium-range forecasting of monsoon rains. *In:* J. Lighthill and R.P. Pearce (eds), Monsoon Dynamics, Cambridge University Press.

Pisharoty, P.R. (1981). Sea-surface temperature and the monsoon. *In:* J. Lighthill and R.P. Pearce (eds), Monsoon Dynamics, Cambridge University Press.

Sharma, T.C. (2000). Drought parameters in relation to truncation level. *Hydrological Processes*, **14**, pp. 127-128.

Sin, H. and Salas, J.D. (2000). Regional drought analysis based on neural networks. *ASCE J Hydrological Engineering*, **5(2)**, pp. 145-155.

Yevjevich, V., Hall, W.A. and Salas, J.D. (1978). Drought research needs. Water Resources Publication, Colorado.

3

Water Resources

Rainfall contributes to an estimated 65% of global food production, while water for irrigation provides the remaining 35% for the 17% of total agriculture area of the world. Rainfall alone is not sufficient to grow crops and the food production in rain-fed areas as its daily/monthly/annual variation is significant. Failing rains result in droughts and water/crop yield deficits, while the excessive rains cause flooding and crop losses. It is estimated that on an average, 45% of water is used by the crop, with an estimated 15% lost in the water conveyance system, 15% in the field channels and 25% in inefficient field applications (FAO, 1994). Most of the water loss (40%) occurs at farm and field level that has a direct effect on crop production due to inadequate water supplies causing water stress or excessive water and resulting in reduced growth and leaching of plant nutrients. Water scarcity is expressed as the ratio between water demand or withdrawal and water availability. A threshold of 0.4 of water demand/availability ratio is often taken as indicator for Severe Water Scarcity. Overview of the methods and their utility in the drought assessment scenario is highlighted in this chapter.

3.1 Water Scarcity

Water scarcity may be the most underestimated resource issue facing the world today and the world water demand has increased three-fold over the last half-century and signs of water scarcity have become common. Historically, water shortages were local. Water-scarce countries or regions often satisfy the growing needs of cities and industry by diverting water from irrigation and importing grain to offset the resulting loss of production. 70% of world water use, including all the water diverted from rivers and pumped from underground, is used for irrigation, 20% is used by industry, and 10% goes to residences. Irrespective of over-pumping from its aquifers, China is developing a grain deficit.

Drying Rivers and Lakes

Some of the more widespread indicators are rivers running dry, wells going dry, and lakes disappearing. Among the rivers that run dry for part of the year are the Colorado in the United States, the Amu Darya in Central Asia, and the Yellow in China. China's Hai and Huai rivers have the same problem from time to time, and the flow of the Indus River – Pakistan's lifeline – is sometimes reduced to a trickle when it enters the Arabian Sea. The Colorado River, the largest in the southwestern United States, now rarely makes it to the sea. As the demand for water increased over the years, diversions from the river have risen to where they now routinely drain it dry. A similar situation exists in Asia, where the Amu Darya – one of the two rivers feeding the Aral Sea – now is dry for part of each year. With the sharp decline in the amount of water delivered to the Aral Sea by the Amu Darya, the sea has begun to shrink. There is a risk that the Aral could one day disappear entirely, existing only on old maps. China's Yellow River, the northernmost of its two major rivers, first time ran dry for a few weeks in 1972. Since 1985, it has failed to make it to the Yellow Sea for part of almost every year. Sometimes the river does not even reach Shandong, the last province it flows through en route to the sea. As water tables have fallen, springs have dried up and some rivers have disappeared entirely. China's Fen River, the major watercourse in Shanxi Province, which once flowed through the capital of Taiyuan and merged with the Yellow, no longer exists. Another sign of water scarcity is disappearing lakes. In Central Africa, Lake Chad has shrunk by some 95 percent over the last four decades. Reduced rainfall, higher temperatures, and some diversion of water from the streams that feed Lake Chad for irrigation are contributing to its demise. In China, almost 1000 lakes have disappeared in Hebei Province alone.

Falling Water Table

Water tables are falling in several of the world's key farming regions, including under the North China Plain, which produces nearly one third of China's grain harvest; in the Punjab, which is India's breadbasket; and in the U.S. southern Great Plains, a leading grain-producing region. North Africa and the Middle East, Algeria, Egypt, Iran, and Morocco are being forced into the world market for 40 percent or more of their grain supply due to water shortage. We are consuming water that belongs to future generations. In some places, the fall of water tables is dramatic. Nature of aquifer depletion in select countries is shown in Table 3.1. Some of the micro level revenue units of different states in India are grouped based on their groundwater withdrawal (Table 3.2). Iran is facing widespread water shortages. In the northeast, Chenaran Plain – a fertile agricultural region to the east of Mashad, one of Iran's largest and fastest-growing cities – is fast losing its water supply. Wells drawing from the water table below the plain are used for irrigation and to supply water to Mashad. Falling water tables in parts of eastern Iran have caused many wells to go dry. Some villages have been evacuated because there is no longer any accessible water. Iran is one of the first countries to face the prospect of water refugees – people displaced by the depletion of water supplies. In Yemen water tables are falling everywhere by two metres or more a year. The capital Sana'a's extraction exceeds recharge

Table 3.1: Aquifer depletion status in select countries

Country	*Region*	*Description of Depletion*
China (Michael Ma, 2001)	North China Plain	Water table falling by 2-3 metres per year under much of the Plain. As pumping costs rise, farmers are abandoning irrigation.
United States of America (Postel et al., 1999)	Southern Great Plains	Irrigation is heavily dependent on water from Ogallala aquifer, largely a fossil aquifer. Irrigated area in Texas, Oklahoma, and Kansas is shrinking as aquifer is depleted.
Pakistan (Tushaar Shah et al., 2000)	Punjab	Water table is falling under the Punjab and in the provinces of Baluchistan and North West Frontier.
India (Tushaar Shah et al., 2000)	Punjab, Haryana, Rajasthan, Andhra Pradesh, Maharashtra, Tamil, Nadu, and other states	Water tables falling by 1-3 metres per year in some parts. In some states exatraction is double the recharge. In the Punjab, India's breadbasket water table falling by nearly 1 metre per year.
Iran (Hamid Taravati, 2002)	Chenaran Plain, northeastern Iran	Water table was falling by 2.8 metres per year but in 2001 drought and drilling of new wells to supply nearby city of Mashad dropped it by 8 metres.
Yemen (Christoper Ward, 2001)	Entire country	Water table falling by 2 metres per year throughout country and 6 metres a year in Sana'a basin. Nation's capital, Sana'a, could run out of water by end of this decade.
Mexico (Tushaar Shah et al., 2000)	State of Guanajuato	In this agricultural state, the water table is falling by 1.8-3.3 metres per year.

Table 3.2: Groundwater exploitation level status water resources of Mandal/Block/Tehsil/watershed of India

State	*Total Mandal/Block/ Tehsil/Watershed*	*No. Mandals/Blocks/Tehsil/Watershed*			
		Over exploited		*Dark/Critical*	
		No.	*%*	*No.*	*%*
Andhra Pradesh	1157	118	10.20	79	6.83
Bihar	394	6	1.52	14	3.55
Delhi	6	3	50.00	1	16.67
Gujarat	180	41	22.78	19	10.56
Haryana	111	30	27.03	13	11.71
Karnataka	175	7	4.00	9	5.14
Kerala	151	3	1.99	6	3.97
Madhya Pradesh	312	2	0.64	1	0.32
Maharashtra	2316	154	6.65	72	3.11
Rajasthan	237	86	36.29	80	33.76
Tamilnadu	385	138	35.84	37	9.61
Uttar Pradesh	819	2	0.24	20	2.44
West Bengal	275	0	0.00	61	22.18
Daman & Diu	2	1	50.00	1	50.00

Source: Planning Commission, Govt. of India

by a factor of five, dropping the water table by six metres a year and wells drilled to a depth of two kilometres failed to find any water. In the absence of new supplies, the Yemeni capital will run out of water by the end of this decade. Egypt is entirely dependent on the Nile River and it is reduced to a trickle as it enters the Mediterranean. In Mexico, the demand for water has outstripped supply in many states. Mexico City's water problems are legendary. In the agricultural state of Guanajuato, the water table is falling by 1.8-3.3 metres a year.

Climate Variation

Water resources are highly sensitive to climate variability and change. Not only socio-economic aspects of society will be affected by changes in water availability, but also government policies in its response. The often inordinate 'demands' for irrigation water, especially where it is subsidized, can be reduced by better recharge and conveyance practices, drip or sprinkler application of water, better timing of irrigations, and improvements in crop management including genetic changes and better knowledge of true water needs. Many technological practices can reduce the impact of drought (Rosenberg, 1986). Many water-demand reductions have been proven in such semi-arid lands as Israel and Australia: water harvesting, better on-site retention, and so on. In order to meet the ever increase in demand, water harvesting planning and management is required for arid and semi-arid zones where the present difficulties are due to the limited amount of rainfall and their inherent degree of variability associated with it. In temperate climates, the standard deviation of annual rainfall is about 10-20 percent for 13 years out of 20 years of data analysis. In arid and semi-arid climates the ratio of maximum to minimum annual amounts is much greater. It becomes increasingly skewed with increasing aridity. With mean annual rainfalls of 200-300 mm the rainfall in 19 years out of 20 typically ranges from 40 to 200 percent of the mean and for 100 mm/year, 30 to 350 percent of the mean. At more arid locations it is not uncommon to experience several consecutive years with no rainfall.

3.2 Critical Issues in Water Resources

In the arid and semi-arid regions, rainfall variability, individually or per chance annual, seasonal and sub-seasonal periodicities, affect the livelihood system of farmers leading to severe drought conditions. As a coping mechanism farmers diversify crop system (primary production system), rely on secondary production system (livestock) and tertiary production systems (non-farm occupations) that are less sensitive to rainfall fluctuations. Where climatic change might increase rainfall and raise the level of groundwater, hydraulic management can be applied, as in the Netherlands and Finland. The critical issues are: (1) Spatial and temporal variation in precipitation – Given the large potential demand for water resources of the country, a holistic local, regional and national level management strategy is desired; (2) Change in global climate – Global climate change caused by progressive warming trend is likely to contribute in the changing rainfall pattern; (3) Appropriate management regime based on agro-climatic and basin wide approach is desired as they affect the utility of water resources in farming system and involvement of multiple stake holders; (4) Declining role of traditional water management structures and institutions – Tank irrigation is cost effective and also managed predominantly by the users themselves; (5) Disparity in irrigation spread across regions could be attempted using agro-climatic classification as basis of development; (6) Projection of future water demand needs to be situated within a decision framework that is guided by the principles of sustainability development; (7) 75 to 80% of irrigated production is contributed by ground water. Progressive decline in groundwater table has forced farmers for enhanced investment and forced to abandon the wells that are of very poor yield of water; (8) Community participation (ground water company) in the groundwater use could reduce over-exploitation by fixing appropriate cropping pattern; and (9) Poor water efficiency is also one of the main reasons for over-exploitation of ground water.

Human Activities

Unintentional human activities (land use) modify the natural hydrologic system. It may also intervene in the natural hydrologic processes: precipitation, infiltration, storage and movement of soil moisture, surface and subsurface runoff, recharge of ground water and evapotranspiration. The various factors that may affect system are highlighted here. *Land factors* such as morphology, soil, and plant cover factors determine the storage of water on the surface or in the soil, percolation to ground water, evaporation, and runoff. Their role is particularly significant over short periods of time in humid areas; their effects in arid and semi-arid lands are long-lasting. In arid and semi-arid areas the impact of land factors on evaporation can exceed those of climatic variation. *Soil temperature and moisture* quickly respond to a change in atmospheric circulation. The quantity of plant-available water that can be held in the root zone of most crops is of the order of 100 mm, which in the growing season can sustain crop growth only for a short time; moisture stress begins to reduce photosynthetic production after less than a week of dry weather. Farmers understand the role of the soil-moisture and of the spacing between rainstorms in semi-arid region and are aware that increase in the number of stress days would have an immediate impact on crop yield. *Stream flow* has a relatively short turnover period and is a major source of fresh water. For small catchments or low flows, the variability of surface flow is amplified, because runoff is a residual of precipitation and evaporation, and its variability surpasses the variability of precipitation, particularly in areas with little runoff. *Groundwater* – Longer and sustained periods of climatic fluctuations affect first the shallow groundwater resource. Domestic wells and the base flow in small streams used for stand-by irrigation go dry leading to lowering of pumps. Further, longer fluctuations have an impact on deep aquifers, reducing water pressure, permitting compaction and resulting in land subsidence. Over-pumping gives an indication of the impact of prolonged drought or reductions in aquifer recharge. Groundwater storage, a useful cushion over short fluctuations in climate, is vulnerable to long fluctuations.

3.3 Hydrological Process

The development and successful application of hydrological models for semi-arid and arid regions are seriously hampered by: (1) high degree of spatial and temporal variation in hydrometeorological variables and resulting stream flow; (2) lack of adequately long or continuous records of rainfall (hydrometeorological variables) and stream flow; (3) lack of information on land use changes and their water utilization; and (4) lack of quantitative understanding of the mechanisms of some critical hydrological process (channel transmission loss and surface groundwater interactions). Major water supplies and large storages involving large drainage basins are rarely required in arid/semi-arid regions. The *accuracy of arid/semi-arid stream flow* data is generally low as a result of: (1) isolation of most of the monitoring station and low population density; (2) high variability of rain and irregular occurrence of stream flow; (3) lack of suitable natural control sections in stream with moveable beds and high cost of artificial controls; and (4) harsh climatological and physical conditions. Stream channels in arid zone are dry for a large percentage of time and when runoff does occur, a large portion of the flow is absorbed by the bed and banks. Such channel losses can be sufficient to cause the stream to disappear altogether before reaching its ultimate outlet. *Estimation of peak flows and water levels* is derived on probabilistic basis if sufficient data are available. Simulation of events by way of missing records of synthesization is hardly required. Analysis of recorded events is often involved in model calibration. The vegetation condition vary depending on the amount of rainfall over a preceding period that can vary from few months to several years. *Evaporation and transpiration* in arid regions commonly account for at least 95% of the precipitation. Evaporation from dry soil assumes greater importance relative to transpiration from plants. Soil water storage will be empty at the beginning of a regime of storm events and will often decrease the impact of errors in estimating soil water losses between storms.

Rainfall-runoff

When rain falls, the first few drops of water are intercepted by the leaves and stems of the vegetation growth and referred as interception storage. As the rain continues, water reaching the ground surface infiltrates into the soil until it reaches a stage where the rate of rainfall (intensity) exceeds the infiltration capacity of the soil. Schematic diagram showing the rainfall-runoff relation is shown in Fig. 3.1. Surface puddles, ditches, and other depressions are filled (depression storage) prior, to runoff generation. The infiltration capacity of the soil depends on its texture and structure, as well as on the antecedent soil moisture content (previous rainfall or dry season). The initial capacity (of a dry soil) is high but, as the storm continues, it decreases until it reaches a steady value termed as final infiltration rate. The process of runoff generation continues as long as the rainfall intensity exceeds the actual infiltration capacity of the soil but it stops as soon as the rate of

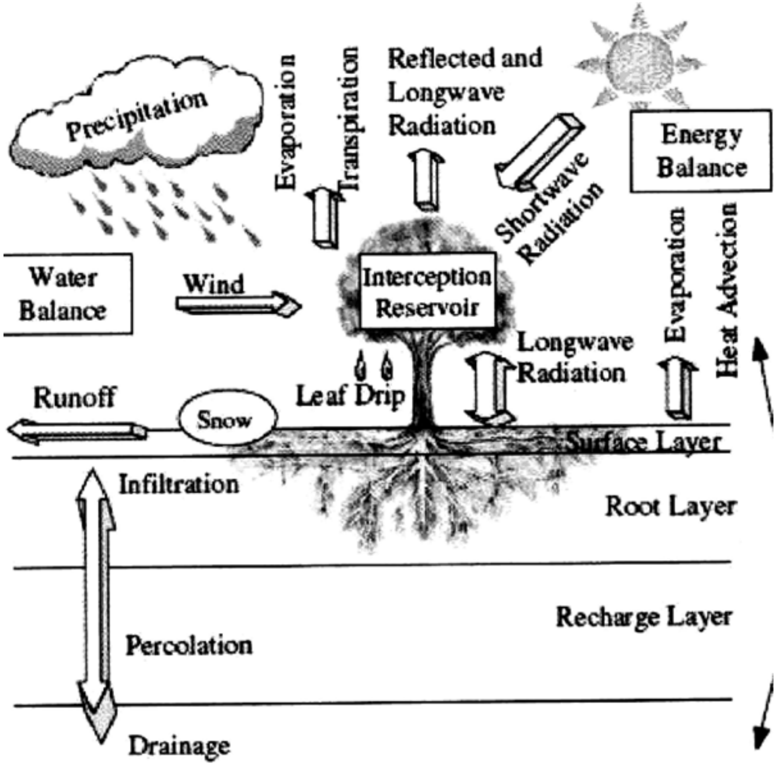


Fig. 3.1: Land surface rainfall-runoff models.

rainfall drops below the actual rate of infiltration. The following aspects of arid and semi-arid regions need greater attention in the run-off estimation: (1) Rainfall tends to be more variable in space and time. Long periods may cause changes in the vegetation and structure of the soil especially on the surface that may have an appreciable effect on infiltration and runoff production; (2) Base flow is absent and channel transmission losses are of critical importance; (3) Model parameters need to be changed for a prolonged wet or dry sequence; (4) There is a relative absence of organic matter and litter on the surface; (5) Plant cover is sparse and consists mainly of xerophytes and ephermeral grasses and small leafy plants; (6) Water table is typically below strata beds and is disconnected from surface drainage system; and (7) A temporary saturated hydraulic connection may occur in flood events.

Rainfall run-off estimation must take into account *the transmission loss* which varies from point to point along a channel and with the degree of saturation of the alluvium in the channel prior to runoff events. Partial-area run off takes place due to differences in infiltration capacity and areas producing run-off in valley bottom and along stream channels. Lower infiltration capacities are caused due to coarser, more compact rock rubble in gullies in one area and fine material washed into valley bottoms by previous events. Short-time *ponding* results in the rapid onset of runoff after the start of rain and the production of runoff with small depths of rains. Cordery et al. (2000) found runoff whenever it was 16 mm of rain in a storm event or when there was more than 5 mm in an hour in Western South Wales. Appreciable *recharge of aquifers from general infiltration* occurs only in extreme events in most of the arid and semi-arid regions. Significant contributions to subsurface water may result from transmission losses. The water may remain in the alluvium beneath the channel or may move into more widespread connected aquifers. *Hydrographs* in arid and semi-arid regions tend to be flashy with short time bases and steep rising and falling limbs. Times of rise are often very short. Hence steepness of the hydrographs and their general characteristics should be considered. *Threshold rainfall* represents the initial losses due to interception and depression storage as well as to meet the initially high infiltration losses that depend on the physical characteristics. In areas where the land is very regularly shaped and having sparse vegetation, the threshold rainfall will be in the range of 3 mm and exceeds to 12 mm where the prevailing soils have a high infiltration capacity. *Design rainfall* is defined as the total amount of rain during the cropping season at or above which the catchment area will provide sufficient runoff to satisfy the crop water requirements and it is determined by means of a statistical probability analysis. If the actual rainfall in the cropping season is below the design rainfall, there will be moisture stress in the plants; if the actual rainfall exceeds the design rainfall, there will be surplus runoff which may result in damage to the structures.

3.4 Water Requirement

Precipitation provides part of the water crops need to satisfy their transpiration requirements. The soil, acting as a buffer, stores part of the precipitation water and returns it to the crops in times of deficit. In humid climates, this mechanism is sufficient to ensure satisfactory growth in rain-fed agriculture. In arid climates or during extended dry seasons, irrigation is necessary to compensate for the evaporation deficit due to insufficient or erratic precipitation. Net water requirements in irrigation are defined as the volume of water needed to compensate for the deficit between potential evapotranspiration and effective precipitation over the growing period of the crop. It varies considerably with climatic conditions, seasons, crops and soil types. For a given month, the crop water balance can be expressed as:

$$\text{IWR} = Kc \times ET_0 - P - \Delta S$$

where IWR is net irrigation water requirement needed to satisfy crop water demand; Kc – coefficient varying with crop type and growth stage; ET_0 – reference evapotranspiration, depending on climatic factors; P – precipitation; and ΔS is change in soil moisture from previous month.

In the specific case of paddy rice irrigation, additional water is needed for flooding to facilitate land preparation and for plant protection. In that case, irrigation water requirements are the sum of rainfall deficit and the water needed to flood paddy fields.

3.5 Water Balance under Natural Conditions

The estimation of the water balance for an average year is based on three digital geo-referenced data sets for precipitation, reference evapotranspiration and soil moisture storage properties. The computation of water balance is carried out by a model with a 10 km or less spatial resolution (depending upon the data availability) of grid-cells and in monthly time steps. The results consist of annual values by grid-cell for actual evapotranspiration, runoff and water stored as soil moisture. For each grid cell, actual evapotranspiration (Eta) is assumed to be equal to the reference evapotranspiration (Eto), calculated for each cell with the Penman-Monteith method in those periods of the year when precipitation exceeds reference evapotranspiration or when there is enough water stored in the soil to allow maximum evapotranspiration. In drier periods of the year, lack of water reduces actual evapotranspiration to an extent depending on the available soil moisture. Evapotranspiration in open water areas and wetlands is considered to be equal to reference evapotranspiration throughout the whole calculation period. For each grid cell, runoff is calculated as the part of the precipitation that does not evaporate and cannot be stored in the soil. Runoff is always positive except for areas identified as open water or wetland, where actual evapotranspiration can exceed precipitation. The method is calibrated by comparing calculated values for water resources per country (i.e. the difference between precipitation and actual evapotranspiration) with data on water resources for each country obtained from AQUASTAT country surveys. In addition, the discharges of major rivers given in the literature have been compared with the calculated runoff for the drainage basin of these rivers. Where the calculated runoff values did not match the values available in the literature, correction factors have been applied to one or more of the basic input data on precipitation, reference evapotranspiration, soil moisture storage and open water.

3.6 Irrigation Water

The impact of irrigation on water resources requires an estimate of the volume of water extracted from rivers, lakes and aquifers for irrigation purposes. It normally far exceeds the consumptive use of irrigation because of water lost in its distribution from its source to the crops. The ratio between the estimated irrigation water requirements and the actual irrigation water withdrawal is often referred to as "irrigation efficiency". It also implies that the water is being wasted when the efficiency is low. The unused water can be used further down-stream in the irrigation scheme; it can flow back to the river or it can contribute to the recharge of aquifers. Hence, "water requirement ratio (WRR)" will be used to indicate the ratio between irrigation water requirements (IWR) and the amount of water withdrawn (AWW) for irrigation.

$$\mathrm{WRRr} = \mathrm{IWRr}/\mathrm{AWWr}$$

where suffix r is for the region; WRR – the water requirement ratio for the region; IWR – the total irrigation water requirement for the countries in the region; and AWW – the total agricultural water withdrawal for the region. Libya and Saudi Arabia are using volumes of water for irrigation which were several times larger than their annual water resources. China is facing severe water shortage in the north while the south still has abundant water resources.

Annualized irrigated areas (AIA) are computed based on, first, determined cropping seasonality or intensity (single crop, double crop, continuous crop) and then multiplying the full pixel areas (FPAs) of the various seasons with irrigated area fractions (IAFs) for that season. This will give us the sub-pixel areas (SPAs), which are actual areas irrigated for the season. By adding SPAs of season 1, season 2, and "continuous" we will get AIA. *Seasonal irrigated areas* (SIA) is the sum of areas irrigated during season 1 (June-October), season 2 (November-February), and continuous (crops such as sugarcane or plantation crops such as orchards) which leads to AIA. The SIA is equivalent to "net seasonal" (e.g., khariff, rabi) irrigated areas reported in some national statistics. *Total area available for irrigation* (TAAI) is the sum of areas actually irrigated in a season (e.g., season 1) and the area left fallow (but equipped for irrigation) during the same season (e.g., season 1). It includes (a) irrigated areas at the time when the imagery was taken (e.g., season 1), and (b) fallow areas at the time when the imagery was taken (e.g., season 1). Note that the fallow areas are also equipped for irrigation, but are not irrigated during the season in consideration (e.g., season 1). China (31.5%) and India (27.5%) lead irrigated areas of the world. The next leading irrigated area countries (as a percentage of the global annualized sum of 480 Mha) are USA (5%), Russia (3.5%) and

Pakistan (3.3%) followed by nine countries (Argentina, Australia, Bangladesh, Kazakhstan, Myanmar, Thailand, Turkey, Uzbekistan and Vietnam) between 1 and 2%. *Irrigation intensity* – The irrigation intensity is obtained by dividing the AIA with TAAI. The global irrigation intensity is 117%. China and India are 141% and 132% respectively. The irrigation intensities of USA, Russia, and Pakistan are 117%, 129%, and 123%, respectively. *Irrigation source* – Globally, 61% of all irrigation is from surface water and 39% from ground water and/or conjunctive use. In India there is 38% surface water irrigation and 62% groundwater and/or conjunctive use irrigation. *Crop characteristics* – Crop calendar, cropping intensity and crop dominance for every irrigated area class.

3.7 Ground Water

70% of drinking water supplies of the European Union and 80% of rural water supplies in Sub-Saharan Africa depend on ground water. In India ground water supplies about 80% of rural population and 70% of Indian agricultural production is supported by ground water. Over-exploitation of ground water and related activities such as resource depletion, quality deterioration, drying up of wetlands and lean season flows in streams and rivers are critical issues in several countries including Mexico, China (especially the North China plains), the United States, Spain, Iran and Jordan. These countries have tried a variety of strategies to control groundwater overdraft by farmers. Mexico's new water law made groundwater a national property. China, which does not have private ownership rights on farmland, has always treated groundwater as national property. In the United States, groundwater regulation is a state subject but started 50 years earlier in some states. Urban groundwater depletion has been dealt with effectively in many countries. However, in no country has regulation of groundwater use for agriculture been very effective. In China, the new water law mandates that tube well owners in villages have to get a water withdrawal permit and pay a fee. China has 4.5 million agricultural tube wells; so enforcing the permits is administratively difficult. But Mexico has only 90,000 agricultural tube wells; and even there the government has found it impossible so far to enforce a system of concessions on private tube wells.

Regulating groundwater draft from 20 million agricultural wells through administrative and legislative means in India would be difficult. Usually surfacewater transported from a distance is offered as a substitute for ground water. During the past decade, many cities in North China have been able to ease pressure on urban aquifers by first developing a captive surface water reservoir to supply the cities, followed by a campaign to decommission urban tube wells. In the United States too, California, Arizona and many other states in the western part of the country have been able to ease pressure on groundwater only by organising long distance transport of new surface water and supplying it to farmers and towns. In Mexico, recognizing the impossibility of enforcing groundwater quotas on farmers, the government has begun using pricing and supply of electricity as an indirect lever to regulate pumping of ground water. Farmers have to pay a penal charge for power they use for pumping water beyond their stipulated quota of groundwater draft and appear to be working in select places. Linking of north and southern rivers in India is a step in this direction.

Aquifer

Rocks with moderate to high permeability allow considerable flow of ground water and are called aquifers (water-bearers). Aquifers can occur at various depths. Those closer to the surface are more likely to be exploited for water supply and irrigation. Rates of groundwater flow depend on the composition of the rock containing the ground water (the aquifer). Schematic diagram showing the groundwater aquifer and their nomenclature is shown in Fig. 3.2. Permeable rocks such as sands, gravels and some types of limestone allow rapid water flow but impermeable layers such as clay can limit the flow rate – to less than a metre per year. Rocks such as clays, shales, silts and unfractured crystalline rocks are aquicludes – their permeability is so low that they form barriers to groundwater movement. An *unconfined aquifer* is one where the upper boundary of the groundwater body is the water table and the ground water is fed by recharge from the unsaturated zone. Alternatively, a *confined aquifer* is one where the aquifer is overlain by an *aquiclude* and so there is no water table: the water cannot find its own level but is forced to stay below the overlying layer. If more water is extracted from an aquifer than is recharged, the water table is lowered and subsidence of the land can follow as the previously saturated ground dries and shrinks. On the other hand, when deep-rooted vegetation is removed and/or irrigation is used, the water table can rise and dissolved salts and minerals are brought to the surface and left there when the water evaporates, causing the problem known as *dry land salinity*. In some areas, the rising water table brings dissolved salts to the surface, causing salinity problems. Draining wet, low-lying land for housing or agriculture destroys wetlands and moves water from one place to another, for example to drainage sumps, other wetlands or rivers and excessive use of shallow groundwater can lower the water table and dry out wetlands some distance away from the bores. Lowered water tables can damage native vegetation and wetland ecology.

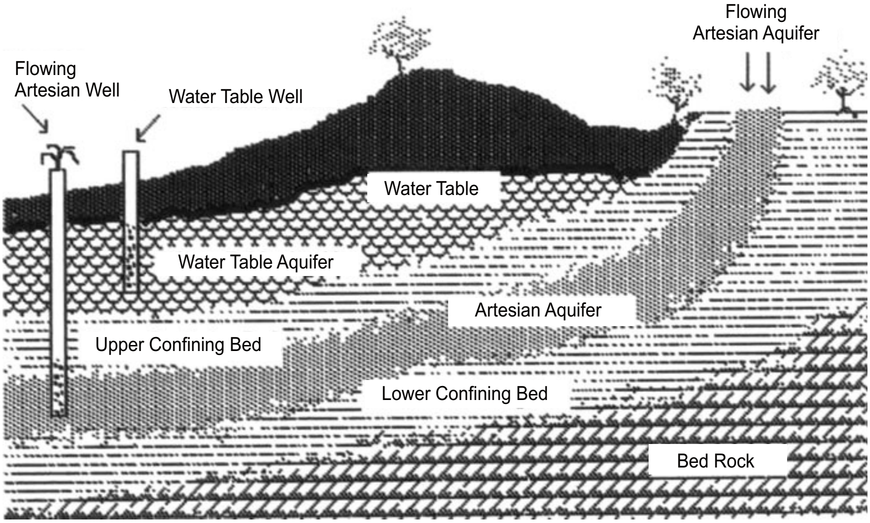


Fig. 3.2: Schematic diagram showing the groundwater aquifer and their nomenclature.

Unconfined aquifers are sometimes also called water table or phreatic aquifers, because their upper boundary is the water table or phreatic surface. Typically the shallowest aquifer at a given location is unconfined, meaning it does not have a confining layer between it and the surface. Unconfined aquifers usually receive recharge water directly from the surface, from precipitation or from a body of surface water (e.g., a river, stream, or lake) which is in hydraulic connection with it. Confined aquifers have the water table above their upper boundary (an aquitard or aquiclude), and are typically found below unconfined aquifers. Confined aquifers have very low storativity values (much less than 0.01, and as little as 10^{-5}), which means that the aquifer is storing water using the mechanisms of aquifer matrix expansion and the compressibility of water, which typically are both quite small quantities. Unconfined aquifers have storativities (typically then called specific yield) greater than 0.01 (1% of bulk volume); they release water from storage by the mechanism of actually draining the pores of the aquifer, releasing relatively large amounts of water (upto the drainable porosity of the aquifer material, or the minimum volumetric water content). The term “perched” refers to ground water accumulating above a low-permeability unit or strata, such as a clay layer. The difference between perched and unconfined aquifers is their size (perched is smaller).

Ground water can be found at nearly every point in the earth’s shallow subsurface. They do not necessarily contain fresh water. In a saturated zone or phreatic zone (e.g., aquifers, aquitards, etc.) all available spaces are filled with water, while in an unsaturated zone (also called the aeration), there still exists pockets of air with some water that can be replaced by water. Saturated means the pressure head of the water is greater than atmospheric pressure (it has a gauge pressure > 0). The definition of the water table is surface where the pressure head is equal to atmospheric pressure (where gauge pressure = 0). Unsaturated conditions occur above the water table where the pressure head is negative (absolute pressure can never be negative, but gauge pressure can) and the water which incompletely fills the pores of the aquifer material is under suction. The water content in the unsaturated zone is held in place by surface adhesive forces and it rises above the water table (the zero gauge pressure isobar) by capillary action to saturate a small zone above the phreatic surface (the capillary fringe) at less than atmospheric pressure. This is termed tension saturation and is not the same as saturation on a water content basis. Water content in a capillary fringe decreases with increasing distance from the phreatic surface. The capillary head depends on soil pore size. In sandy soils with larger pores the head will be less than in clay soils with very small pores. The normal capillary rise in a clayey soil is less than 1.80 m (six feet) but can range between 0.3 and 10 m (1 and 30 ft). The capillary rise of water in a small diameter tube is the same physical process. The water table is the level to which water will rise in a large diameter pipe (e.g. a well) which goes down into the aquifer and is open to the atmosphere.

An aquitard is a zone within the earth that restricts the flow of ground water from one aquifer to another. An aquitard can sometimes, if completely impermeable, be called an aquiclude or aquifuge. Aquitards comprise layers of either clay or non-porous rock with low hydraulic conductivity. In mountainous areas (or near rivers in mountainous areas), the main aquifers are typically unconsolidated alluvium. They are typically composed of mostly horizontal layers of materials deposited by water processes (rivers and streams), which in cross-section (looking at a two-dimensional slice of the aquifer) appear to be layers of alternating coarse and fine materials. Coarse materials, because of the high energy needed to move them, tend to be found nearer the source (mountain fronts or rivers), while the fine-grained material will make it farther from the source (to the flatter parts of the basin or over bank areas – sometimes called the pressure area). Since there are less fine-grained deposits near the source, this is a place where aquifers are often unconfined (sometimes called the fore bay area), or in hydraulic communication with the land surface. Parts of the Atlas Mountains in North Africa, the Lebanon and Ante-Lebanon ranges of Syria, Israel and Lebanon, the Jebel Akhdar (Oman) in Oman, parts of the Sierra Nevada and neighbouring ranges in the United States' South West, have shallow aquifers which are exploited for their water. Libya and Israel's population growth along the coast has led to over-population which has caused the lowering of water table, contamination of the ground water with saline intrusions.

Classification

A map-based aquifer classification system has been developed to support groundwater management to support the water management programmes towards groundwater allocation, planning and protection. Aquifers are categorized based on their current level of use and vulnerability to contamination and a ranking to indicate the relative importance of an aquifer. The level of development of an aquifer is assessed by demand verses the aquifer's yield or productivity – high (i), moderate (ii) and low (iii) vulnerability. The classification component is as follows:

Aquifer classification

Development sub-class			
	I	II	III
	Heavy (demand is high relative to productivity)	Moderate (demand is moderate relative to productivity)	Light (demand is low relative to productivity)
Vulnerability sub-class			
	A	B	C
	High (highly vulnerable to contamination from surface sources)	Moderate (moderately vulnerable to contamination from surface sources)	Low (not very vulnerable to contamination from surface sources)
Aquifer class			
	I	II	III
A	IA – heavily developed and high vulnerable aquifer	IIA – moderately developed, high vulnerability aquifer	IIIA – lightly developed, high vulnerability aquifer
B	IB – heavily developed, moderate vulnerable aquifer	IIB – moderately developed, moderate vulnerability aquifer	IIIB – lightly developed, moderate vulnerability aquifer
C	IC – heavily developed, low vulnerability aquifer	IIC – moderately developed, low vulnerability aquifer	IIIC – lightly developed, low vulnerability aquifer

A numerical ranking value is determined by summing the point values for each of the following hydro-geologic and water use criteria – productivity, size, vulnerability, demand, type of use, quality concerns and quantity concerns. All the criteria have arbitrarily been assigned equal weight. Values range from minimum of 1 to maximum of 3 except for quality and quantity. Possible ranking scores range from low of 5 to a high of 21; the higher the ranking score, the greater the aquifers's priority. An inventory database containing the attributes of each aquifer is built as aquifer and are identified and classified.

Ranking component

Criteria	*Point values*			*Rationale*
	1	2	3	
Productivity	Low	Moderate	High	Abundance of resource
Vulnerability	Low	Moderate	High	Potential for water quality degradation
Size	< 5 sq. km	5 - 25 sq. km	> 25 sq. km	Regionality of the resources
Demand	Low	Moderate	High	Level of reliance on the resource supply
Type of use	Non-drinking water	Drinking water	Multiple/ drinking water	Variability/diversity of the resource for supply
Quality	Isolated	Local	Regional	Actual concerns
Quantity	Isolated	Local	Regional	Actual concerns

Vulnerability

Aquifers are vulnerable to natural hazards and human impacts: Shallow uppermost unconfined aquifers mainly in unconsolidated fluvial and glacial deposits overlain by permeable unsaturated zone of low thickness (less than 10 m), characterized by young groundwater and single flow system and interface with surface water. Deeper unconfined aquifers in consolidated rocks (particularly sandstones) of regional extent, overlain by permeable unsaturated zone of variable thickness, consist usually of a number of laterally and vertically interconnected groundwater flow systems of appreciable dual porosity and permeability. Ground water in karstic aquifers with carbonate rocks flow in conduits, large open fissures and openings along bedding plates; typically with high groundwater flow velocities (hundreds of metres per day) and secondary permeability; springs are important phenomena of groundwater karstic regime. *Coastal aquifers* – in natural conditions seawater intrusion into coastal aquifers is controlled by tidal fluctuations, stream flow changes, gradient and volume of groundwater flow towards the seashore and geological environment. Groundwater pumping influences significantly on ground water-sea water interface. The following types of aquifers are resistant to natural hazards and human impacts: Deep confined aquifers or aquifer systems mostly in sedimentary rocks overlain by thick low permeable or impermeable unsaturated zone with entirely modern recharge which may last hundreds or thousands of years. Deep confined aquifers are overlain by thick low permeable or impermeable unsaturated zone. Ground water originated in geological past and is not part of the recent hydrological cycle. Low intensity of groundwater circulation, very limited aquifer replenishment and very large aquifer storage are typical characteristics of non-renewable groundwater resources. A possible limited criterion for non-renewable ground water could be that the average annual aquifer renewal is less than 0.1% of the aquifer storage – the average renewal period would be at least 1000 years (Margat, 2006). Connate water is entrapped in the sediments of low permeability at the time of their deposition.

Rapid increase in the use of ground water, for irrigation, has contributed significantly to agricultural and overall economic development. The present global groundwater withdrawal rate is of 600-700 km^3/year. In arid and semi-arid regions, ground water is the most important safest source of drinking water and the world strongly depends on it. In many arid and hard-rock zones, increases in overdraft areas and associated water-quality problems are emerging. Groundwater mining also occurs at the local level in several other countries of the Near East, South and East Asia, Central America and in the Caribbean. When the rains stop and surface water resources dry up, ground water becomes the only water source available for drinking and irrigation purposes. As a result boreholes and open dug wells that were previously utilized within a sustainable level are over-used at a time of diminished recharge leading to drop in water level. The extent of aquifer depletion (regional or local) is controlled by aquifer's permeability. Changes in recharge will result from changes in effective rainfall as well as change in the timing of the rainfall season. Indirect impacts on groundwater resources also arise from patterns.

Groundwater Exploitation Status Indicators

Groundwater indicators based on monitoring and assessment programmes support sustainable management of groundwater resources. The following groundwater indicators are proposed for global, national or aquifer levels by Vrba and Zaporozec (1994). Ground water is often overlooked in drought analysis, even though there is an increasing demand and reliance on ground water growing from population, agriculture and industrial requirements. The information currently available to managers, planners and stakeholders is primarily in raw data form (well records, water chemistry etc.) or isolated studies in specific areas. Recharge activities and much more work is needed to depict its effects on a spatial and temporal variability on local and regional scales and to be evaluated at regular intervals.

1. *Renewable groundwater resources per capita* indicates the water consumption per capita. Trends with respect to social development and economic growth. Available renewable ground water resources (m^3 per year).

$$\text{GW Renewable Recharge} = (\text{Recharge} + \text{Seepage} - \text{Base flow} + \text{inflow}) - (\text{inflow} + \text{artificial recharge})$$

2. *Groundwater abstraction ratio* is used in creation of water stress scenarios. It is critical to determine the recharge as realistically and accurately as possible. Attention should be paid to time used for recharge calculation, particularly for arid and semi-arid regions, where heavy event rainfall may be more meaningful than weaker but regular rainfall.

Total groundwater abstraction/Groundwater recharge × 100%

Scenario 1 – Abstraction ≤ recharge (< 90%),
Scenario 2 – Abstraction = recharge (100%),
Scenario 3 – Abstraction > recharge (>100%).

Groundwater recharge is defined as an addition of water to a groundwater reservoir. Total abstraction includes total withdrawal of water through wells, boreholes, springs and other ways for the purposes of public water supply and agriculture, industrial and other usages.

3. *Total groundwater abstraction/exploitable groundwater resources* helps in linking the total volume of ground water that can be abstracted annually to groundwater recharge estimates and recognize possible over abstraction.

Total groundwater abstraction/Exploitable groundwater recharge × 100%

4. *Groundwater as a percentage of total use of drinking water* expresses the present state and trends of surface water and ground water use for drinking and other purpose. In arid and semi-arid zones, ground water is the most significant and safe source of drinking water. It plays a fundamental role in the social development of rural areas.

5. *Groundwater depletion* indicates how much water can be withdrawn from a groundwater body without producing an undesired impact on ground water (excessive depletion of river base flow, ecological impacts in wetlands, irreversible changes to biotopes, subsidence in unconsolidated sediments and intrusion of water of poor quality). Declines in the groundwater hydraulic head reflected in the increase of pumping costs, decreasing well production and make groundwater use economically and socially unfeasible.

6. *Groundwater level declines* and groundwater storage is depleted due to exploitation. It has to be evaluated with reference to natural and seasonal fluctuation from the influence of climatic conditions and aquifer characteristics. Regional groundwater level declines due to high density of production wells (detect a consistent and gradual downward trend of water level from a well monitoring network or compare the levels with two different periods), change of base flow due to groundwater depletion (presence of phreatic vegetation or wetlands suffer notable changes), land subsidence and change of groundwater quality characteristics (change in age and origin of ground water at specific locations).

$$\sum \text{Area with groundwater depletion problem} / \sum \text{Area of studied aquifers} \times 100$$

Sum of area with groundwater depletion problem (observed regional water level decline due to exploitation). Sum of area of studied aquifers means the total area subject to consideration.

Potential groundwater depletion problem can be identified when regional aquifer level declines are associated to: (a) areas with a high density of production wells (loss of production well yields indicates groundwater depletion in areas with a high density of wells); (b) change of base flow – drastic reduction of groundwater flux and loss of base flow is associated with groundwater depletion (indirect evidence is pheratic vegetations or wetlands suffer notable changes); (c) change of groundwater quality characteristics – changes in age and origin of groundwater specific locations in the aquifer along with physical-chemical properties of water; and (d) land subsidence – groundwater exploitation from thick unconsolidated aquifer-aquitard systems suffer from significant land subsidence indicating an unsustainable groundwater exploitation.

7. *Total exploitable non-renewable groundwater resources/annual abstraction of non-renewable groundwater resources* records the stress and that indicates the lifetime of non-renewable (fossil) groundwater resources that have no present-day recharge or very low recharge.

Total exploitable non-renewable groundwater resources (m^3)/annual abstraction of non-renewable groundwater resources (m^3/area).

It is an effective quantification that could be used for the management of groundwater resources development and as an early warning of overexploitation. Ground resources evaluation is calculated from hydrogeological, geophysical and isotope hydrological investigations and abstraction is calculated as a mean value over a significant range of years.

8. *Groundwater vulnerability* is a relative, non-measurable, dimensionless property that reports the natural (or intrinsic) vulnerability as a function of hydrogeological factors – the characteristics of the aquifer and the overlying unsaturated geological material and the soil (recharge, soil and unsaturated zone properties, groundwater level below ground and saturated zone hydraulic conductivity). *Groundwater vulnerability* (net recharge, soil properties, unsaturated lithology and thickness, groundwater level below ground, aquifer media and aquifer hydraulic conductivity in addition to topographic slope) is a relative non-measurable dimensionless property. GOD empirical system for the rapid assessment of aquifer vulnerability includes evaluation of G: groundwater occurrence, O: overall aquifer class and D: depth to groundwater table. It is divided into five classes from negligible (deep confined aquifer) to extreme (shallow water table aquifers).

9. *Groundwater quality* informs the present status and trends in space and time of water quality related to naturally occurring and anthropogenic contamination.

$\sum$ Area of aquifer with groundwater natural-quality problem/
$\sum$ Area of studied aquifers × 100% = Natural quality

$\sum$ Area with increment of concentration for specific parameters/
$\sum$ Area of studied aquifers × 100% = Anthropogenic problem

Natural quality problems are associated with chemical water composition (WHO) related to iron, chloride, chromium, selenium and other inorganic species. Anthropogenic problems are estimated from diffuse source contamination problems due to agriculture activities and urban on-site sanitation etc.). Physical-chemical parameters such as electrical conductivity, nitrate and chloride along with ^{18}O, ^{2}H, ^{14}C and ^{15}N indicate the dynamic process of groundwater quality change due to natural and human impacts. Constraints related to extrapolation of groundwater quality from wells at regional scale include: (a) Deep wells generally mix water of different levels that may have different origins and composition; (b) Irregular distribution of wells in an area causes difficulties for identifying groundwater contamination in the whole aquifer; and (c) Problems due to poor construction and maintenance of wells cause well contamination which is not necessarily due to aquifer contamination.

10. The *total annual abstraction of ground water* means the total withdrawal of water from a given aquifer by means of well, bore holes and other artificial ways for the purpose of domestic water supply and irrigation. The annual abstraction should be calculated as a mean value over a significant range of years. This could change from year to year. Two main criteria which define non-renewable groundwater resources are: (a) mean annual recharge should be less than 0.1% of stored volume and (b) exploitation of the groundwater concerned should not have a significant impact on neighbouring renewable systems or recharged groundwater bodies. Non-renewable groundwater systems are located in arid regions of Northern America, Arabian Peninsula and Australia and under permafrost conditions of Western Siberia.

11. *Groundwater quality* with respect to drinking water standards, irrigation requirements, industrial use and others forms an indicator. It makes it possible to identify and to foresee the outcome of processes leading to groundwater contamination.

12. *Dependence of agricultural population on ground water* is an important indicator in arid and semi-arid regions as it signifies the livelihood and household home support of rural people.

The precision of this information depends on the reliability of the information and data gathering. It is appreciated well by preparedness and mitigation and public if it is made in the quickest possible time. Groundwater level monitoring activities carried out are being used in preparing this index. Representative water wells for each region will be used for monitoring groundwater levels. The monthly levels are compared with values equivalent to the 25th, 10th, and 5th percentiles of historical records. Groundwater levels in confined aquifers are responsive to pumping stresses at distances far removed from pumping centres. No baseline exists for measuring changes in water levels for confined systems. Therefore percentile frequencies are not available for wells in these systems. Evaluation of drought impacts in these systems will have to be analyzed as a departure from the long-term downward trend in water levels. Withdrawals exceeding 20% of renewable water supply has been used as an indicator of water stress in initiating water resource legislation and management.

The aquifer classification maps provide land use planners with groundwater information that can both support planning processes and help protect and sustain the resource. It is possible that there are areas within the moderately vulnerable aquifer that are highly vulnerable. *Highly vulnerable aquifers (A)* require planners to consider activities that minimize the risk of contamination (e.g., zoning for a park rather than for industry) or to require safeguards to protect the resource or preventive measures and more stringent standards for operation. *Moderately vulnerable aquifers (B)* may or may not be suitable for land uses that pose a high risk of groundwater contamination. No zoning change for a higher risk use over a B aquifer should be considered until the level of vulnerability for that specific site has been assessed. *Low-vulnerable aquifers (C)* are more likely to be considered for land uses that are high risk to groundwater than A and B. The definition of an aquifer's level of development is based on a combination of supply and demand factors. The aquifer's productivity, the demand placed on it, and the areal extent (size) of the aquifer are used in assessing the impact of increased water withdrawal on the aquifer for the proposed land uses. *Heavily developed aquifers (I)* indicate the existing high demands on the groundwater resource and it is to be assessed to determine whether new wells could be constructed without affecting the ability of existing wells to withdraw water. *Moderately developed aquifers* should be able to support more groundwater withdrawals than heavily developed aquifers. *Lightly developed aquifers* shall be able to accommodate greater demand on their water supplies than either of the previous two categories of aquifer development.

3.8 Water Recharge

Recharge from direct precipitation and by induced infiltration of surface water involves the vertical movement of water under the influence of vertical head differentials. The quantity of vertical movement varies from place to place and it is controlled by the vertical permeability and thickness of the deposits through which infiltration occurs, the head differential between sources of water and the aquifer, and the area through which leakage occurs. Shallow, surficial aquifers (sand-and-gravel and bedrock) do not have water stored in overlying deposits from which they can draw during times of drought. Therefore, water levels in such aquifers are more sensitive to climate conditions and will decline in response to dry weather. Available drawdown in wells (the difference between the non-pumping water level and the allowable pumping level, such as the top of the well screen or the pump intake) will be correspondingly reduced. The situation can be exacerbated further by the effects of well interference; water demand often increases during drought, causing wells to be operated at higher pumping rates and/ or for longer periods and increasing the drawdown at neighbouring wells.

The amount of water that infiltrates into the soil varies with the degree of land slope, the amount and type of vegetation, soil type and rock type, and whether the soil is already saturated by water. The regolith is the layer of loose unconsolidated material, including soils, sediments, and rock fragments, that overlies bedrock and forms the surface of the land. Ground water is recharged through infiltration from precipitation and through leakage from the bottom of some rivers and lakes. In some cases it is ground water which provides the water for wetlands. In general, shallow groundwater flow is towards nearby rivers or springs, where it seeps to the surface to form stream flow, but deeper ground water may flow beneath catchments to form regional flow systems. The distribution of groundwater recharge is also uneven vertically, enhanced by differing hydraulic properties of the aquifer system. Recharge occurs in desert regions though highly irregular in time and space, and at very low rates (<5 mm/a); in semi-arid and tropical regions with major annual fluctuations and a range from less than 30 mm/a to some 150 mm/a; in humid regions at an average of less than 300 mm/a; and even through permafrost, albeit minimal. Numerical modelling for typical sequences of hydraulic conductivities in aquifer systems shows that on an average more than 85% of the recharged groundwater discharges through near-surface (active recharge zone), and less than 15% through deep aquifers (passive recharge zone). Both of these generalised recharge zones in turn overly connate water and are encountered in all continents, climate zones and rock types. Ground water in the active recharge zone is young (<50 years), quite susceptible to contaminants and reaches steady state conditions fairly rapidly if extraction does not exceed groundwater recharge. In the passive recharge zone, ground water is always older (>100 years), the longer time scales ensuring better protection against contaminants, provided that groundwater management takes account of depth related groundwater recharge; otherwise a transient hydraulic response may last decades or hundreds of years. This delayed mass transfer can be monitored through early warning systems. In the passive recharge zone, ground water could be more mineralised (higher ionic concentration) than in the active recharge zone, and sometimes is characterized by rare dissolved elements (e.g. arsenic, iodine, fluoride), because of high mean turn-over times, resulting in slower leaching than in the active recharge zone.

3.9 Sustainability of Water

Indicators of water sustainability are: (1) *Water availability* – proportion and volume of water derived from ground water, surface water and reclaimed water resources; and frequency and duration of water shortages. (2) *Water usage* - daily and total municipal water usage by sector; municipal household water consumption patterns; authorised versus actual groundwater abstraction; and number of water trading licences issued, and volume of water traded. (3) *Supply water quality* – conserve and enhance public health; human health criteria exceedances. (4) *Water disposal* - proportion of municipal population served by treated wastewater; percentage and amount of effluent disinfected – by disposal and reuse of treated wastewater; volume of sludge from wastewater treatment plant disposed or reused; and volume of storm water treated and discharged to receiving waters or reused. (5) *Receiving water quality* – conserve and enhance aquatic ecosystems and associated environments; guideline trigger levels reached in inland waters; and pollutant loadings to marine environments from storm water and wastewater pipes and drains, which exceed environmental health regulations. (6) *Flow implications*: Conserve and manage water resources; ratio of groundwater abstraction to groundwater recharge; and river discontinuity. (7) *Satisfy economic and institutional constraints* - expenditure on water supply; expenditure on wastewater treatment and disposal; cost of water supply and disposal under conventional versus ‘greener’ urban water systems; and investment ratio in ‘greener’ wastewater, storm water and groundwater management practices, as a proportion of total wastewater, storm water and groundwater expenditure. (8) *Social and political expectations* - already listed within indicators 1-7. (9) *Promote reuse*, recycling and sustainable water use proportion of grey water, storm water and black water recycled/reused; proportion of wastewater reused (before/after). (10) *Reaching wastewater treatment plant* – composite indicator: management effort; and number of people involved in community water monitoring programmes.

3.10 Groundwater Supply Systems

Community groundwater supplies are derived from a wide variety of aquifer types. Shallow (<100 ft) and deep sand-and-gravel (unconsolidated) aquifers and shallow and deep bedrock (consolidated) aquifers. Sand-and-gravel aquifers are the result of glacial deposition or are found as alluvial deposits within the valleys of modern river systems. Sand-and-gravel aquifers may be less than 10 to several hundred feet thick. They may occur at the land surface (surficial aquifers) or be buried beneath 100 feet or more of glacial overburden or fine-grained alluvium. Surficial aquifers typically are unconfined and water levels in wells completed in these aquifers reflect water table conditions. Because of their direct connection to land surface, recharge to these aquifers is dependent upon infiltrating precipitation, and, therefore, these aquifers are susceptible to drought. Deeper sand-and-gravel aquifers, confined beneath deposits of finer-grained materials, largely depend upon recharge as slow leakage from overlying deposits, and thus are less sensitive to drought as long as the overlying source beds can furnish water to the underlying aquifer systems.

Yields of wells in sand-and-gravel aquifers are highly variable, from ten gallons per minute (gpm) or less to over 1000 gpm. Well yields are dependent upon the water-transmitting ability of the formation, which is largely a function of pore size and pore interconnectedness. Extremely large well yields (1000+ gpm) are common in thick, very coarse-sized, deposits. Where deposits are thin or composed of fine sands, well yields may not exceed 10 gpm. Sand-and-gravel aquifers probably provide the greatest proportion of water to small communities, principally because they can be tapped economically and are capable of supplying adequate amounts of water for the typically smaller demands of communities less than 10,000 population. Bedrock aquifers also occur and like sand-and-gravel aquifers, are highly variable in their ability to yield water to wells. Yields of crystalline and carbonate bedrock aquifers depend on fracture density and secondary porosity developed along fractures. Bedrock aquifers range in type from fractured crystalline rocks to carbonate rocks of limestone or dolomite to sandstones. Surficial bedrock aquifers, just like their sand-and-gravel counterparts, are susceptible to drought.

3.11 Crop Yield and Groundwater Abstraction

Crop yield and quality are strongly linked to water supply at key growth stages. In areas that have historically had an adequate soil water supply, without recourse to irrigation, there is a risk that as water abstraction rates increase and water levels fall, agricultural yields may decrease and organizations with responsibility for water abstraction may find themselves facing claims for compensation. Other work considering abstraction in relation to soil moisture work has sought to assess the scale of irrigation practices and to spatially quantify the volume of water abstractions or developed maps of soil moisture based on purely biophysical, climatic data. However, soil water and aquifers depend inherently on the underlying geology and for arable crops, the depth of the rooting profile.

Water level at the open dug well and bore wells are being monitored by agencies and are used in the preparation of water level contours that represent the pre- and post-monsoon conditions. It is observed that return flow from the agriculture plots contribute to the water level in a well. Water level information from these wells could be expressed on a map and used along with soil moisture in understanding the drought situation, based on the depth to water below ground level and the crop root system and five classes of agronomy constraints leading to water stress. Permeability information representing the soil, hard soil and weathered rocks would influence water recharge movements. Four risk classes could be defined with the help from expert knowledge of agricultural practice in terms of their depth in mbgl as follows: Class 1: *Water table shallower than 1.5 mbgl*; Possible impact on wetland habitats and agricultural crops abstracting soil moisture to a maximum depth of 1.5 mbgl, e.g. potatoes, onions, carrots, vegetable brassicas, peas, beans and established grassland on mineral soils. Class 2: *Water table between 1.5 and 2.5 mbgl*: No impact on vegetation or crops in Class 1. Possible impact on deeper rooting agricultural crops abstracting soil moisture to a maximum depth of 2.5 mbgl, e.g. cereals, oilseed rape, maize, sugar beet and perhaps grassland growing on peaty soils. Class 3: *Water table between 2.5 and 4.0 mbgl*: No impact on vegetation or crops in Classes 1 or 2. Possible impact on established trees. Class 4: *Water table deeper than 4.0 mbgl*: Lowering of water table by groundwater abstraction from the sandstone aquifer will not impact significantly upon soil moisture availability to any vegetation. The rationale for the selection of these criteria was to create a Soil Moisture Vulnerability map that represented the worst-case scenario, that is one where the water table is represented as close to the surface as it is ever likely to be.

Crop Water Budgeting (CWB) is a critical component of the Participatory Hydrological Monitoring (PHM) activity. It is considered as final step in the chain of PHM aiming at sustainable groundwater management by the farmers themselves. *Groundwater balance sheet* for individual revenue villages is drawn based on: the quantity of total water requirement (human livestock and irrigation); water expected from surface storages (river, canal, reservoir and lakes); anticipated groundwater draft for Oct-April and recharge from rainfall for rest of the monsoon year; groundwater available for usage at the beginning of rabi season; groundwater available for the rest of the current monsoon year and projected groundwater balance at the end of current monsoon year, in understanding the quantity of water either deficit or surplus. This analysis portrays the demands from different sectors and supply and self water effective regulation methods under a given situation and also take collective decision regarding the change of crops and methods of irrigation or any other changes in their respective habitations. Deficit or surplus information under a given rainfall and crop area conditions could portray a scenario that would aid in the resource identification and preparedness.

3.12 Stream Flow Analysis

The streams are classified according to their stream flow type that expresses the consistency in flow, which depends on the hydrological system of its catchment and the height of the groundwater table relative to the streambed. Stream flow can either be *perennial*, when water in the stream is continuously flowing and never dries up, *intermittent*, in a channel which at drier times of year may have some reaches with flowing water interspersed with other reaches in which the water flows below the surface, when the flow ceases during the dry season, or *ephemeral*, when flow occurs only directly after a rainfall event (Mosley and McKerchar, 1993). Sometimes confusion exists about how to classify streams, which do not fall dry regularly for a longer period each year during the dry season, but only in some years for several days. The stream flow characterization at different climate zones is described (Fig. 3.3).

Class Af: Tropical - This is a very warm and humid region with relatively high precipitation and temperature values throughout the year. Rain events are usually caused by convection and therefore they are quite strong and occur frequently throughout the year. At higher altitudes there is a second precipitation maximum in July and August (Golden Gate Weather Service, 2003). *Class BW: Dry desert* - The desert climate is characterized by a permanent negative water balance, meaning that evapotranspiration amounts exceed precipitation during the whole year. Rain events occur only a few times per year or not at all, each event lasting only for a couple of days. *Class BS: Dry steppe* - In this region the annual evaporation also exceeds the annual precipitation, but the year consists of a dry as well as a wet

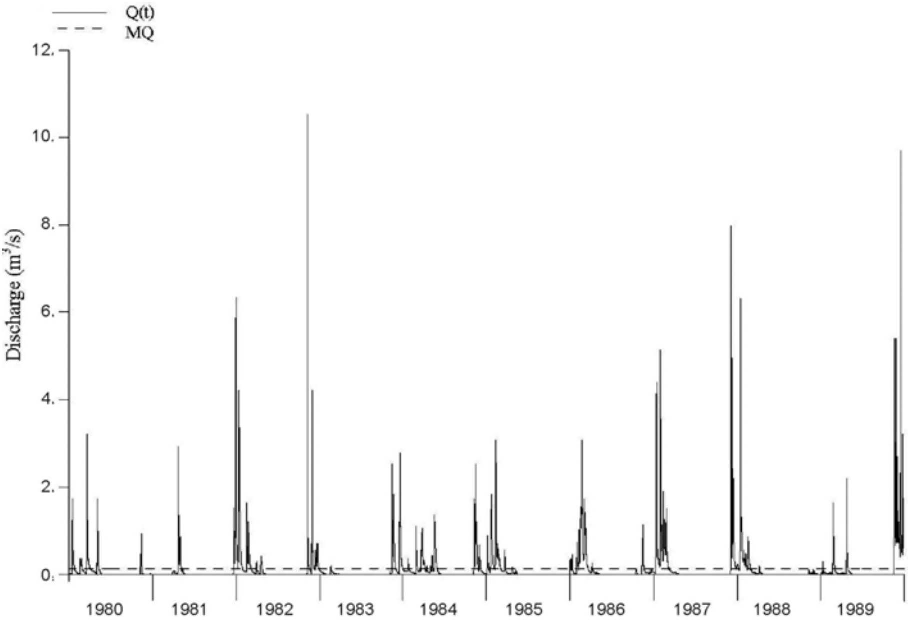


Fig. 3.3: Stream flow characteristics of ephemeral rivers.

season and therefore the negative water balance is not consistent throughout the year. *Class Cw: Temperate, winter dry* – This climate is characterised by a distinct annual cycle of temperature, resulting in winter and summer seasons. Precipitation is relatively low during the winter and high during the summer. The mean annual precipitation amount varies considerably between regions within the Cw climate zone from less than 200 mm/a to more than 10,000 mm/a in the monsoon influenced regions. In most regions it can also happen that in some months during the winter it does not rain at all. *Class Cs: Temperate, summer dry* - The Cs-climate has mostly the same features as the Cw-climate except that the dry period occurs in the summer and the wet period in the winter.

Class Cf: Temperate, no dry season – The Cf-climate is also characterised by a distinct annual cycle of temperature, resulting in a winter and a summer season and similar temperature ranges as in the Cw-climate, but here precipitation occurs during the whole year. Throughout the year precipitation is mostly caused by eastwards migrating anticyclones, which leads to no distinct dry season, while a precipitation maximum still occurs during the winter months. For the three catchments on the northern hemisphere (Ray, Lambourn, Lindenborg) this maximum is extended into the autumn and lasts from September to December while a clear minimum occurs during the spring (Frich et al., 1997; Mühr, 2003). For the two catchments on the southern hemisphere, both in New Zealand, the precipitation maximum lasts from May to August which is the winter and early spring on the southern hemisphere. The two New Zealand catchments also belong to a mountain range which receives high amounts of mean annual precipitation (around 2000 mm), much more than the three catchments of the northern hemisphere. There the mean annual precipitation lies around 650-800 mm.

Class Df: Cold, no dry season - The average temperature of the warmest month in the cold climate region is >10 °C and that of the coldest month is < -3 °C. Precipitation occurs all year around with at least 30 mm in the driest month and little difference between the driest and the wettest months compared to other climate regions. Mean monthly precipitation is the highest from June to October. In the winter months precipitation falls as snow and does not contribute to the discharge of a stream until the snowmelt in spring or early summer. Then it might cause high discharge peaks and even serious flood events. Some rivers in these regions freeze completely during some time in the winter or they freeze over on the surface. When precipitation and water in the catchment get stored in the form of snow and ice, streams experience a continuous low flow period in the winter.

Evaluation of applicability of the MA (*n*-day)-filter as pooling procedure for streams with different streamflow types

Stream flow type	*Evaluation*
Perennial	The MA (*n*-day)-filter can be optimised and used for all perennial streams and drought duration and deficit volumes can be compared. The method here has not been tested in detail, but it can be expected that a moving average interval of $n = 10$ days provides good results for non-flashy streams as suggested by Tallaksen et al. (1997) and as observed for Lindenborg. For the only flashy perennial stream in the global data set a MA(15-day)-filter could be recommended.
Perennial - seasonal	For the summer season the MA (*n*-day)-filter can be used in the same way as for perennial streams without frost influence. Important is how the summer droughts are selected.
Intermittent	The MA (*n*-day)-filter has not been tested for intermittent streams. The suggestion is that during the *wet season* it can be used as for perennial streams and that during the *dry season* pooling is not necessary.
Ephemeral	Pooling is not relevant.

MA: Moving Average

A *streamflow drought* is said to be a period during which the discharge is below normal or, in a demand oriented study, a period during which the discharge is insufficient. It is characterized through low flow values and a clear differentiation between droughts and low flow periods has to be made. The term '*low flow period*' usually refers to the regime of a stream, which represents the average annual cycle of the stream flow, and the terms 'low flow period' and 'high flow period' are used to describe the normal annual fluctuations of stream flow linked to the annual cycle of the regional climate. Depending on the climate, the regime of a stream can show one or more low flow and high flow periods. The equatorial climate for example is marked by two rainy and two dry seasons and streamflow regimes have two corresponding high flow and low flow periods (McMahon and Diaz Arenas, 1982), while a monsoon climate causes only one low flow and one high flow period.

Droughts on the other hand are not necessarily a seasonal characteristic of a stream flow regime. They are prolonged periods with unusually low stream flow, which do not have to occur each year. For example in a Mediterranean region the summer months June till October could be the low flow period of a stream, but only in dry and hot summers the stream would experience droughts. So there can be years passing without the occurrence of any drought events and there can be years when one or several droughts occur. But there exist also droughts which last only a few days and droughts which last several months, several seasons or several years. Often a period of unusually low stream flow has to last a defined minimal period of time to be considered a drought. Depending on the climate of a catchment only periods of below normal discharge compared to the low flow part of the regime are considered to be droughts, whereas deviations from the high flow part are rather called 'streamflow deficiency' or 'stream flow anomaly' (Hisdal, 2001). This is usually the case for a catchment in a temperate climate region, where a stream flow deficiency compared to the high flow part of the regime usually have no severe consequences. In a semi-arid region on the other hand, one is used and prepared to long periods of low or even no streamflow during the dry season and the interest of water management engineers lies in the water quantities of the wet season. In a semi-arid region a drought study might therefore also be focusing on the high flow season and streamflow deficiencies in the high flow season can either be considered as droughts themselves or as the cause of a subsequent drought during the dry season. Drought studies have been based on many different concepts (Hisdal et al., 2004).

One way is to study droughts on the basis of *low flow characteristics* such as a time series of the annual minimum n-day discharge, $AM(n\text{-day})$ or a percentile from the flow duration curve (FDC) (Section 2.2), which describes the low flow part of the regime. To study droughts, extremes of the low flow characteristics are chosen. These approaches identify and characterise droughts only according to one of their statistical properties, which is their magnitude expressed through the discharge (Tallaksen et al., 1997). They do not necessarily look at the discharge as a time depending process or they look only at a predefined period of it, e.g. n days.

The second way of studying droughts is to look at the discharge series as a time depending process and to identify the complete period of a drought event, from its first day to the last one. In this way a series of drought events can be derived from the discharge series and the drought events can be described and quantified by a number of different properties, so called *deficit characteristics*, such as drought duration. One possibility to define drought events is as "the longest periods which are necessary to yield a specified small percentage (1-10%) of the mean annual runoff" (Smakhtin, 2001). The most commonly applied ones, introduce the use of a threshold or truncation level, Q_0. A discharge value is chosen as threshold level and in the most basic form of this concept a stream is defined to be in a drought situation at times when the discharge is below the threshold level. The threshold level element is used in the so-called threshold level method as well as in the Sequent Peak Algorithm (SPA), which are both evaluated in this study.

The properties characterising drought events are called 'deficit characteristics', since they describe a specific period during which the discharge is in a deficit, for example, as compared to the threshold level. The most commonly applied deficit characteristics are the drought's time of occurrence, its duration, its deficit volume or severity, and the minimum flow occurring during the drought event. Sometimes the drought intensity also is considered which is the ratio of the deficit volume and drought duration. The time of occurrence of a drought event has been expressed in several ways, for example as the date of the first day of the drought, the median date or the date of the day with the minimal flow (Hisdal et al., 2004). In regional studies also the areal coverage is of interest and for planning tasks the extreme events and their return periods are very important. One has to be aware that in order to describe a drought or a time series of droughts completely also the chosen threshold level and its meaning have to be mentioned, since for example duration and deficit volume of the detected droughts vary with the chosen height of the threshold level.

3.13 Water Balance Method

The statistical properties of drought occurrence and their severity indices can only be used for long range planning purpose of storage of reservoirs and operation of reservoirs. The storage requirements can be assessed from the concerned drought-duration curves. Extensive flow measurement is required. Estimation of recharge to water table/aquifer and land use factor of the catchment are also important. The water balance equation can be used for detailed analysis of homogenous small catchments. Self-recording instruments measuring groundwater level, rainfall, temperature, surface river flow etc. would enhance the accuracy of water balance equation:

$$\begin{aligned} P = {} & (E + SW_0 + EW + GW_0 + IGW + ISW) - \\ & (SW_i + GW_i + IW + DSW + DGW) \end{aligned}$$

where P is precipitation, SW_0 – surface water outflow, EW - exported water, GW_0 - groundwater outflow, IGW – increase in groundwater storage, ISW – increase in surface water storage, SW_i – surface water inflow, GW_i - ground water inflow, IW - imported water, DSW – decrease in surface water storage and DGW is decrease in groundwater storage.

Continuous modelling of runoff from rainfall under fairly constant basin conditions require a water balance type model in which hydrological processes are simulated. Continuous modelling of the relation between surface hydrology and catchment cover under normal dry/wet period variations is essential.

3.14 Watershed Analysis

A number of authors have considered the influence and importance of basin properties, particularly geology, on low flows. Especially in extreme low flow periods with lack of rain, the geology of a catchment dominates the runoff. Other than precipitation, stream flow is the one hydrologic variable directly related to drought that has been measured using consistent methods. There could be few and incomplete records from state-to-state. Another significant measure of drought impact is groundwater levels and surface water levels at water-supply reservoirs. They are not available uniformly, inconsistent and typically have much shorter periods of record. There is no groundwater level observation network comparable to the stream gauging network. Well observation networks are for a multitude of purposes and are measured across a wide range of frequencies, in a variety of aquifers and non-aquifers (including confined and unconfined systems).

Groundwater level declines are not always correlated directly to water supply except for the shallowest of wells. Stream base flow is closely related to groundwater levels. The analysis of stream flow records was considered to be an efficient manner to evaluate the impacts of historical droughts on the water resources. Knowledge of the hydrological impacts of historical droughts can then be used to characterize and identify potential impacts of droughts on water supplies. Most of the time either well location and historical records and flow records do not match. Two basic criteria were used in selecting these stations: (1) The stream flow record must be at least 50 years in length, which is needed to realistically estimate drought frequencies and record droughts; and (2) The stream flows at these gauges must be considered to have relatively little impact from human activities and water resource projects. The long-term mean flow rate at any stream location is a function of: (1) climate characteristics of the area; (2) size of area drained by the stream; and (3) average annual precipitation amount. For a given climate condition the mean flow rate for a stream usually is directly proportional to the watershed size - larger the drainage area, the greater the stream flow. In areas where there is significant lateral movement of groundwater, hydrogeological factors may also impact the long-term mean flow rate, but few gauging locations selected for analysis in this study are affected significantly in this way. Stream flow rates at gauging locations are expressed in units of cubic feet per second (cfs) or cms.

Some streams are very sensitive to dry conditions. The sensitivity of surface-water supplies to drought is dependent not only on the frequency and severity of droughts, but also on possible connections between groundwater and surface waters that are controlled by surficial geology, topographic position, and other watershed characteristics. The ratios between the average flow during the six-month drought of record (M6,R) and the long-term-mean flow (Qmean) from gauging stations provide a good indication of the extent to which groundwater can provide sustainable low flows on a stream, even during cases of severe drought. Higher values are indicative of stream flow regimes in which groundwater provides the predominant portion of flow in the stream. In contrast, the six-month record low flow for most locations lack a strong ground/surface-water connection and typically is less than 5% of the long-term-mean flow. Streams that have a high groundwater contribution to low flows also have a high potential to act as a water-supply source because they have sustainable flows during drought periods. However, such areas rarely use their streams for water supply, unless a particularly large quantity of water is needed, because they also have plentiful groundwater resources. In contrast, streams that have a low amount of groundwater contribution typically also will lack sufficient shallow groundwater resources for use in water supply. Thus, unless there is a deeper aquifer from which to obtain potable water, water-supply systems in these regions historically have constructed reservoirs to store water for use during periods of extended low flow.

In addition to the magnitude of previously observed record droughts or conceivable worst-case droughts, another factor in water-supply planning is the frequency with which droughts of various magnitudes impact water supplies.

3.15 Surface Storage

Reservoir

The yield from a reservoir or reservoir system is represented as: *Base yield* – minimum specified number of consecutive time intervals that can be abstracted. It initially increases with increased target draft until a stage is reached when the reservoir is unable to yield continuously at the target draft resulting in base yielding lower than the target draft. *Firm yield* – is the maximum base yield. It is likely to be smaller for a longer inflow sequence because there is an increased probability of a more severe low-flow subsequence occurring. *Secondary yield* – is the abstraction in excess of target draft when the reservoir is at full supply level. *Non-firm yield* – is the average yield which can be abstracted from a river reservoir system in excess of base yield but not exceeding target draft. *Average yield* – is the sum of base yield and non-firm yield which can on an average be abstracted from a system. *Total yield* – is the sum of the base, secondary and non-firm yields.

3.16 Lakes Cascade Systems

Traditional tanks have helped in the sustained agricultural production in the dry areas of India, Sri Lanka and South-East Asia for the past 2000 years. They have provided an economical means by way of surface storage of runoff during the rainy season for subsequent release of water for irrigation of crop and other social obligations. Most of these tanks are interconnected forming cascades (Fig. 3.4), allowing surplus water flow from the upstream tank(s) and return flow from the upstream command area(s) to reach the tank that is immediately downstream. This facilitates the effective use or sharing of water in arid and semi-arid regions. They have developed and implemented the management practices aimed at improving effective use/sharing of water. There are 208,000 tanks in India, and 120,000 are found in Andhra Pradesh, Karnataka and Tamil Nadu and union territory of Pondicherry that accounts for 60 percent of the tank-irrigation (1.8 million hectares) in India (Vaidyanathan, 2001). They acted as an active “risk minimization agents/ process”. Historical monuments including tanks, dagobas, stone pillars, stone sluices, Brahmi inscriptions, rock cave hermitages and monasteries scattered over the Walawe basin in Sri Lanka expresses the people’s commitment to water conservation. Village settlement (traditional) plans consist of a tank and agriculture lands below it followed by the huts of the shareholders hidden in the shade of their fruit trees, each under the bund or along the sides of the field and all the waste land lying within the boundaries of the parish or the village.

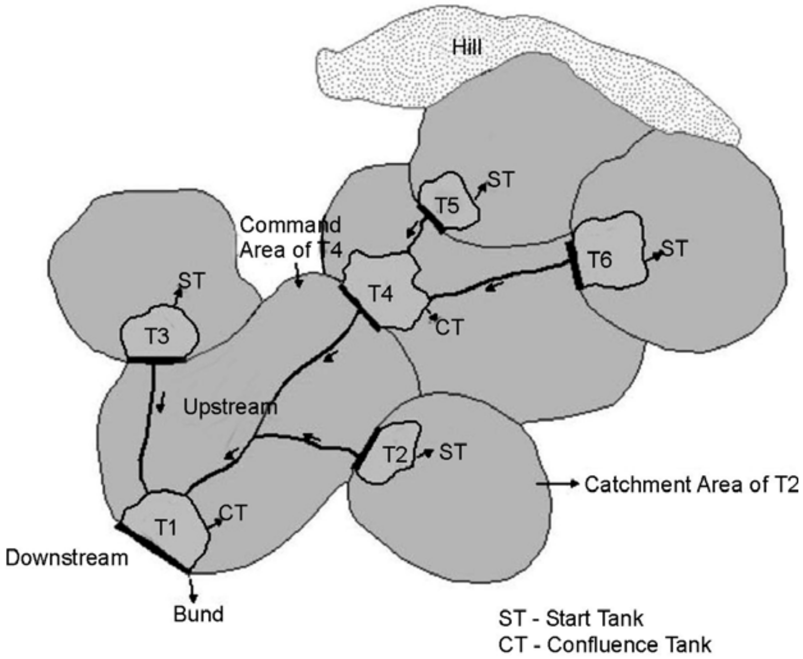


Fig. 3.4: Tank cascade system.

Irrigation and drinking water facilities in a small basin can be improved by: (1) assessing the overall surplus water within the basin by estimating and evaluating outflow from the basin and (2) analyzing the water availability, performance of agriculture and rehabilitation requirements. Interventions from the government, such as popular loans and subsidies, change in cropping preferences of the farmers towards non-food crops and provision of electricity (free or subsidized) for groundwater extraction has led to the increase in groundwater irrigation structures and decline in groundwater levels. Farmers found that groundwater extraction is dependable/risk-free compared to other irrigation sources. This has led to non-recoverable water levels in some areas. With the canal irrigation having already reached closure, the revival of tank irrigation offers a significant supply side intervention to overcome the deficit due to decline in groundwater irrigation. Majority of South India lies in rain shadow regions that receive rainfall of less than 800 mm and has a long history of rainwater harvesting using tanks, which had helped (in the past) in agriculture. The change in climate and weather induces inconsistent rainfall pattern and intensity in arid and semi-arid regions, which are experiencing frequent drought situation. Natural resource conservation and optimal utilization methods are found to be effective in minimizing the impacts of drought.

Status of Tank Cascade

The performance of the tanks is assessed based on its functions: (1) Storage – volume, water loss (evaporation, seepage), siltation level, encroachment (construction, cultivation, reclamation) and vegetation wild growth, (2) Distribution - utility of dead storage, conveyance channels, jack-well, crop production from command area and (3) People's dependability as a source of water. People's willingness to contribute and/or persistence in their demand for rejuvenation of the tanks are the ultimate confirmation of its dependability. It is evaluated by: (1) Cascade water surplus and (2) Water availability for environmental consideration. Some of the observed tanks were not functional due to: (1) Decrease in the tank storage capacity; (2) Tank bed encroachment; (3) Catchment's degradation; (4) Water-quality of stored water supply dependency; (5) Village sewage discharge site; (6) Non-dependability on tank water and development of alternate source availability (bore well) for irrigation and drinking water; (7) Reliance on the new systems of water supply etc. However, significant number of settlements is dependent on the tank system. Hence, the rehabilitation programmes need to consider the benefits in terms of drinking water and areas that could be brought into cultivation.

The said parameters were grouped into classes that could be translated into their part of the integrated Tank Rehabilitation Index (TRI) portraying the existing physical, hydrological and social conditions in helping the decision-making process of rehabilitation. Table 3.3 shows the various physical, hydrological and sociological parameters and their rank/weightage (contribution) to be considered in the decision-making process of rehabilitation of tank. Change in the surface *storage area* (Sa) of tank as demarcated from available thematic maps and other literature over the period is an indication of degradation. The percentage of change is grouped into five classes representing the viability of repairs (>80% not advisable to <20% highly suitable). The present day *depth* (Sd) of the tank represents the sedimentation that has taken place over the years. Average depth to the bottom surface is taken as the deepest level. The removal of silt would enhance the storage capacity that ranges between <25% (minimum silt) and >75% (maximum). Physical condition of the embankment (Ec) needs to be considered while enhancing the storage capacity. The length and number of sections to be strengthened is grouped into four classes where the length of embankment is taken as 100%. Healthiness of the *inflow drainage lines* (Ifd) that convey the runoff from the catchments is important in the filling of the tank. Degradation by way of sand bar, obstruction etc will have an effect on the delivery of water. The length of the drainage having problems is expressed in terms of percentage. Repairing of the maximum length of the stretch would have an effect on the rehabilitation cost. The level and the status of

Table 3.3: Weightage and ranking of parameters for tank rehabilitation

Parameter	*Class*		*Weightage*
Storage area (Sa) (Reduction Percentage)	1	80>	30%
	2	60-80	
	3	40-60	
	4	20-40	
	5	<20	
Depth (Sd) (Reduction Percentage)	1	>75	
	2	50-75	
	3	25-50	
	4	<25	
Condition of embarkment (Ec)	1	>75	
	2	50-75	
	3	25-50	
	4	<25	
Inflow drain condition (Id)	1	>75	
	2	50-75	
	3	25-50	
	4	<25	
Encroachment			15%
Tank bottom occupancy (crop and other activities) (Een)	1	<60	
	2	40-60	
	3	<20	
	4		
Housing (occupation) (Eh)	1	>40	
	2	20-40	
	3	<20	
Crop area and dependency (Cad)	1	>60	15%
	2	40-60	
	3	20-40	
	4	<20	
Drinking water dependent (Dwd)	1	>70 families	10%
	2	50-70	
	3	20-50	
	4	<20	
Catchment degradation (Cdg)	1	>80%	5%
	2	50-80	
	3	20-50	
	4	<20	
Water quality (Wq)	1	Very high	10%
	2	High	
	3	Moderate	
	4	Low	
	5	Clean	
Village sewage drops (Vsd)	1	Untreated	5%
	2	Treated	
	3	Nil	

(*Contd.*)

Table 3.3: (*Contd.*)

Parameter	*Class*	*Weightage*
Critical event supplement		10%
Drinking water (Cewd)	4 >70 families	
	3 50-70	
	2 20-50	
	1 <20	
Irrigation support (CeIS)	4 >60	
(% irrigated area to brought in)	3 40-60	
	2 20-40	
	1 <20	
Rainfall probability (dry)	1 <1yr	
(Rp)	2 2-3	
	3 4-5	
	4 >5	

the *over-flow drain* (Ofd) structure and the feeder lines from tank facilitate the command area irrigation. The percentage of healthiness or degradation of the structures and stretches contribute to the success of the tank cascade system. The *encroachment* (Een) level on the tank bottom deprive the storage capacity. Cultivation, brick-making activities, wild growth of thorny bushes etc. are generally found in the tanks. Their occupancy is measured and used in the assessment. At places the civil structures – *houses and utility* (Eh) structures – have come up. The owners of these structures exert pressure on the administration in abandoning the rehabilitation initiatives. *Cultivated areas* (Cad) were developed around the tank with the hope for development. Other schemes have also neglected these areas assuming that they are dealt by the tank irrigation system leaving these lands totally dependent on the tank water. The economic conditions of the farmers depend on the availability expressed in terms of the total command area.

Command area of the tank depends on the land use/misuse and land degradation. If the land or vegetation cover is degraded, the effective siltation and run-off variation is expected in addition to rainfall-runoff relationship that is being used for estimation. Hence, four classes have been formed in expressing the physical condition. *Families living* around the tank depend on water availability at the tank for drinking purposes. The number of families and animals that rely on the tank source influences the rehabilitation. *Water quality* (Wq) of the tanks is spoiled due to the unchecked contaminators (biological/physical/chemical). Some of the *village sewers* (Vsd) activities can be curtailed or effluents treated prior to discharge. Intensity of pollution decides whether the tank could be worth rehabilitation or not. *Probability of poor Rainfall* (Rp) indicates the anticipated forthcoming events within a year or two based on time series analysis of annual rainfall. This indicates the urgency with which the activities need to be completed. Hence, Tank Rehabilitation Index (TRI)

$$\begin{aligned} \text{TRI} = {} & \Sigma\,[(\text{CeWd} + \text{Rp} + \text{CeIs})] - \Sigma\,[(\text{Sa} + \text{Sd} + \text{Ec} + \text{Ifd} + \\ & \text{Ofd} + \text{Een} + \text{Eh} + \text{Cad} + \text{Dwd} + \text{Cdg} + \text{Wq} + \text{Vsd})] \end{aligned}$$

Assess the spatial and temporal variation of different tanks/cheruvus using thematic maps (historical), orbital satellite data and ground-based information. Figure 3.5 shows drainage network and cascade tank watershed in Addakkal, Mehaboobnagar in India. Identify the factors that are responsible for the degradation and suggest methods of restoration or rehabilitation in enhancing the water storage. Collect the yearly, monthly and daily rainfall information (at least the last one or two decades) and understand their pattern, to be used in the run-off estimation. Estimate the in-coming water onto the different tanks under different rainfall conditions and the out-going. Assess the irrigated areas and the crop type for individual catchment, in addition to the drinking water requirement from the nearby villages. Identify the status of surface water in meeting the requirements of the villages under different annual rainfall conditions. Estimate the anticipated storage, when the silt of known depth (e.g. 1, 2, 3 metre) is removed and used in the field and the cost of removal. Flowchart showing the methodology that is followed in this study is summarized (Fig. 3.6).

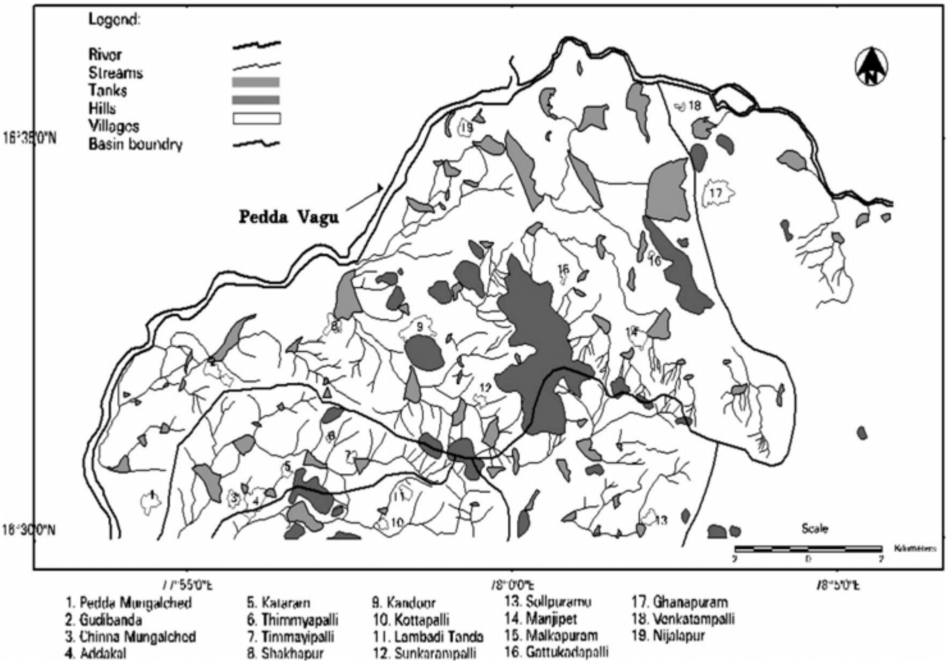


Fig. 3.5: Drainage network and lake cascade watershed.

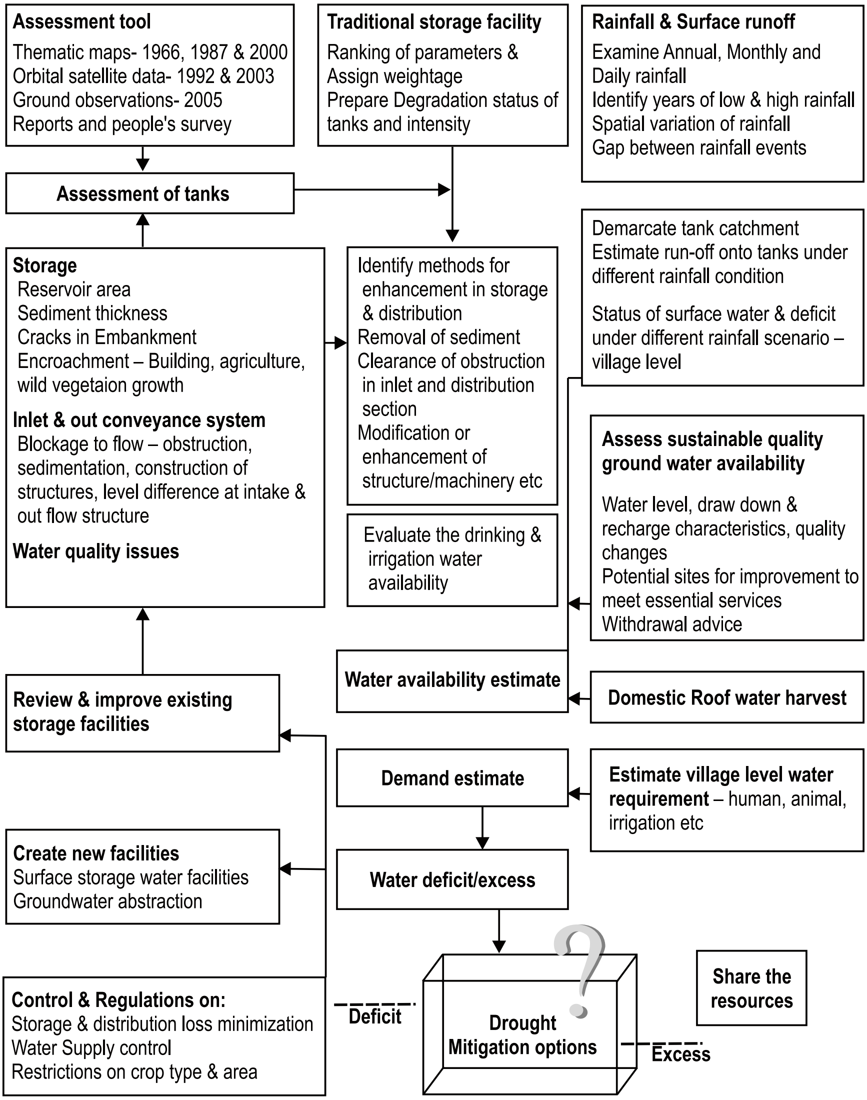


Fig. 3.6: Flow chart showing the drought mitigation options for traditional tank areas.

Tank Cascade Assessment

Cascade water surplus is the quantity of water discharged annually at the base of the cascade after satisfying the present water demand for agriculture as a percentage of total available water-supply to the cascade. It represents the difference between water supply available to the cascade and the present water use adjusted for the scale of total water use. The tank system of irrigation was neglected due to improved irrigation facilities provided by the major and minor dams and its canal system and piped drinking water supply schemes. *Hydrological evaluation* of individual tanks begins with assessment of the water availability, tank storage capacity and agricultural criteria towards the improvement programmes such as set of repair, farmers' proposals and individual tank status. The following indicators are used for this purpose:

1. *Tank water supply adequacy* measures the adequacy and the extent to which the effective runoff (R_o) to tank is adequate to meet the irrigation requirement during monsoon season. If $R_o/I_t > 1$, then tank has adequate water supply to meet the needs.
2. *Tank storage capacity* (S_t) indicates the extent to which the tank is capable of storing the runoff water and releasing it to meet the irrigation requirement (I_t). If the $S_t/I_t > 0.3$, then the tank has the ability to hold 30% of the requirement.
3. *Cropping intensity* (CI_m) measures the extent to which the command area of a tank is cultivated with irrigation water.

The outflow from the tank is achieved by: (1) Cascade screening and grouping based on ratio of cascade area $\mathrm{A_c}$ to the total tank water surface area $\mathrm{A_{cws}}$. (2) Collecting information on tank details – physical, water, agriculture land, season and cropping pattern and intensity, population, groundwater use etc., and evaluate whether the production is affected by water deficit and number of farmers who could benefit from the scheme. (3) Multilevel participatory planning. (4) Estimate the runoffs during normal monsoon and non-monsoon rainfall.

$$S_t = 0.4 \times A_t \times d$$

where S_t is storage capacity; A_t – surface area at full supply; and d – depth at full supply level.

$$R_o = 0.2738\, A_{tca} - 1.4861\ (r^2 = 0.73)$$

where R_o is the effective runoff for an individual tank; A_{tca} – ratio of tank catchment to water spread area; and A_{twa} is hydrological potential of the tank.

Tank system irrigation water demand I_t is related to tank command area A_{tco} by the equation:

$$I_t = 5.7947 + 0.7078\, A_{tco}\ (r^2 = 0.42)$$

The ratio of tank storage capacity, S_t to tank irrigation water demand I_t is related to tank depth d and the ratio of tank water surface A_{tws} to tank command area A_{tco} with the regression equation:

$$S_t/I_t = 0.157 \times 2 + 0.1703x + 0.3218$$

where $x = 1.22\ (A_{tws}/A_{tco}) = 0.62d - 1.52\ (r^2 = 0.85)$

The cascade outflow R_c, is related to the cascade area A_c, total tank water surface area in the cascade A_{cws} and the total command area in the cascade A_{cca} with the regression equation:

$$\log R_c = 1.4582 + 0.0003\ (A_c - A_{cca})\ (r^2 = 0.44)$$

The cascade outflow for rehabilitation planning of an average or above-average rainfall year is required for planning, environmental conservation and downstream user's investment purposes. To evaluate the cascade water surplus, determine the cascade outflow per unit area $R_{e'}$ as the cascade outflow $R_{c'}$ divided by cascade's total area $A_{c'}$.

$$R_{e'} = R_{c'}/A_c$$

Water surplus of cascade $WS_e = R_e/R_{50}$
where R_e is outflow per unit area and R_{50} mean annual rainfall. If this ratio is greater than five percent then the cascade has surplus water that could be refined after field measurements.

Hence, the water availability assessment through the surface river flow characteristics such as lean or full flow methods or surface run-off potential of rain events or groundwater aquifer aspects would ensure the availability for progressive uses. Assessment of the existing systems would help in drought management efforts – whether to create a new storage system or renovate the existing system and adopt effective people's participation in managing their water resources for the settlements and irrigation requirements in semi-arid and arid environment. Crop production needs uninterrupted water supply during its growth phase in addition to fertile soil, healthy (disease-free) environment and good seeds. Various aspects of soil condition, crop growth and the water demand are described in the next chapter.

References

Cordery, McCall (2000). A model for forecasting droughts from tele connections. *Water Resources Research*, **36(3),** pp. 763-768.

FAO (1994). Water for life. World Food Day, Rome.

Frich, P., Rosenørn, S., Madsen, H. and Jensen, J.J. (1997). Observed Precipitation in Denmark, 1961-90. *DMI Technical Report*, **97-8**, Golden Gate Weather Service (retrieved July 2003) http://ggweather.com/normals/HI.htm.

Hisdal, H., Clausen, B., Gustard, A., Peters, E. and Tallaksen, L.M. (2004). Event Definitions and Indices. *In:* Tallaksen, L.M. and Lanen, H.A., J. van (eds.), Hydrological Drought – Processes and Estimation Methods for Streamflow and Groundwater. Developments in Water Science, 48. Amsterdam, Elsevier Science.

Mosley, M.P. and McKerchar, A. (1993). Streamflow. *In:* Maidment, D.R. (ed.), Handbook of Hydrology. McGraw-Hill, Inc., New York, NY, 8.1-8.39.

Mühr, B. (2003). Klimadiagramme weltweit. http://www.klimadiagramme.de

Rosenberg, N.J. (1986). A primer on climatic change – Mechanisms, trends, and projects. Washington DC, Resources for the future paper RR86-04, 19 p.

Smakhtin, V.U. (2001). Low flow hydrology – A review. *Journal of Hydrology*, **240**, pp. 147-186.

Tallaksen, L.M. and Hisdal, H. (1997). Regional Analysis of Extreme Streamflow Drought Duration and Deficit Volume. International Association of Hydrological Sciences. Publication no. 246, pp. 141-150.

Tallaksen, L.M., Madsen, H. and Clausen, B. (1997). On the definition and modeling of streamflow drought duration and deficit volume. *Hydrological Sciences-Journal-des Sciences Hydrologiques*, **42(1)**, pp. 15-33.

Vaidyanathan, A. (2001). Tanks of South India. Centre for Science and Environment, New Delhi.

Vrba, J. and Lepponen, A. (2007). Groundwater resources sustainability indicators, IHP Series on Groundwater No. 14, UNESCO, Paris. pp. 114.

Further Reading

Abayasinghe, A. (1982). Minor Irrigation in Sri Lanka. *Economic Review*.

Bhattacharyya, G.K. and Johnson, R.A. (1977). Statistical Concepts and Methods. Wiley, New York.

Bonacci, O. (1993). Hydrological identification of drought. *Hydrological Processes*, 7, pp. 249-262.

Central Ground Water Board (1983). Ground potential mapping of Mahbubnagar, Andhra Pradesh.

Demuth, S. (1989). The Application of West German IHP Recommendations for the Analysis of Data from Small Research Basins. FRIENDS in Hydrology, International Association of Hydrological Sciences, Publication no. 187, pp. 47-60.

Geological Survey of India (2000). Mahbubnagar district, Andhra Pradesh. District source map, GSI, Calcutta.

Gustard, A., Roald, L.A., Demuth, S., Lumadjeng, H.S. and Gross, R. (1989). Flow Regimes from Experimental and Network Data (FREND), Vol 1, Hydrological Studies, UNESCO-IHP III, Project 6.1, Institute of Hydrology, Wallingford.

Hisdal, H., Stahl, K., Tallaksen, L.M. and Demuth, S. (2001). Have streamflow droughts in Europe become more severe or frequent? *International Journal of Climatology*, **21**, pp. 317-333.

Lovett, A.A., Lake, I.R., Hiscock, K.M., Sunnenberg, G., Foley, A., Evers, S. and Fletcher, S. (2001). Defining groundwater protection zones in England and Wales. *In:* Protecting Groundwater: Proceedings of an International Conference on Applying Policies and Decision Making Tools to Land-Use Planning, Birmingham.

Margat, J., Foster, S. and Loucks, P. (2006). Non-renewable groundwater resources: A guidebook on socially sustainable management for water policy-makers. UNESCO-IHP VI, Series on Groundwater, No. 10.

McMahon, T.A. and Diaz Arenas, A. (eds.) (1982). Methods of computation of low streamflow. *Studies and Reports in Hydrology*, **36**, UNESCO, 122.

Montery County Water Resource Agency (retrieved July 2003) http://www.co.monterey.ca.us/mcwra/deir_svwp_2001.

Oliver, M.A. (1991). Disjunctive kriging: An aid to making decisions on environmental matters. *Area*, **23(1)**, pp. 19-24.

Rivoirard, J. (1994). Disjunctive Kriging and Non-Linear Geo-statistics. Clarendon Press, Oxford.

Sekar, I. and Palanisami, K. (2000). Modernized rain fed tanks in South India. *Productivity*, **41(3)**, pp. 444-448.

Shankari, U. (1991). Tanks – Major problems in minor irrigation. *Economic and Political Weekly*, **V26(39)**, pp. A115-A124.

Stahl, K. and Demuth, S. (1999). Linking Streamflow Drought to the Occurrence of Atmospheric Circulation Pattern. *Hydrological Sciences Journal*, **44(3)**, pp. 467-482.

Stahl, K. and Hisdal, H. (2004). Hydroclimatology. *In:* Tallaksen, L.M. and Lanen, H.A.J. van (eds). Hydrological Drought – Processes and Estimation Methods for Streamflow and Groundwater. Developments in Water Science, 48, Amsterdam, Elsevier Science.

Vogel, R.M. and Fennessey, N.M. (1994). Flow-Duration Curves. I: New Interpretation and Confidence Intervals. *Journal of Water Resources Planning and Management,* **120(4)**, pp. 485-504.

Yevjevich, V. (1983). Methods for determining statistical properties of droughts. *In:* Yevjevich, V., da Cunha, L., Vlachos, E. (eds.), Coping with droughts. Colorado, Water Resources Publications, pp. 22-43.

Zelenhasic, E. and Salvai, A. (1987). A Method of Streamflow Drought Analysis. *Water Resources Research*, **23(1)**, pp. 156-168.

4

Agriculture

Water availability is the factor most critical in determining plant survival, development, and ultimate productivity. Moisture for crops comes from precipitation and from irrigation (for about 40% of the cropland). Weather risk in agriculture is viewed as the uncertainty created in earnings due to weather variability. Long-term seasonal precipitation trends always demonstrate a great season-to-season variability with periodic droughts, which in turn indicate a periodic risk to crop yield, reduced production, and potential income reduction. In the case of agricultural drought, the disaster results from a deficiency in the available moisture in the soil. Even during drought events of short duration and low intensity, the reduction of seasonal moisture essential for plant growth and development might result in low yields and the possibility of reduced incomes. This chapter highlights the soil, crop water requirement, crop irrigation needs and options under water stress conditions.

4.1 Soil

Crop production of an area is dependent on the quality of soil on the 100 cm (top) surface of the earth and seeds, suitability of crop, availability of irrigation facilities and susceptibility to pest and insecticides in addition to continuous monitoring and management practices. Any soil can be put under irrigated agriculture permanently with due care and caution. Certain soils may be beyond economic limits. The ideal soil for irrigation for most of the crop plants except rice is deep, without any water-table, has high water-holding capacity, infiltration rate and permeability, and low salt content. Climate and soil type determine different patterns of drought which are more or less detrimental to yield and requires specific breeding and farming adaptations. They are – early drought affecting the uppermost soil layers responsible for poor seedling establishment and crop failure, drought during the vegetative period resulting in low leaf area index, biomass and grain number and later drought affecting grain (yield and quality). There is great variability among soils of tropical areas. Some are deep and friable and easily tilled while others, such as the lateritic soils, are often thought quite worthless from an agricultural point of view. The warmer and more humid the climate, the speedier biological processes, the more quickly the natural fertility of the soil is used up, and the greater the effort required in maintaining their fertility. Chemical nutrients used up by crops and lost through leaching have to be replenished and great care should be taken to maintain the physical soil fertility by keeping the level of organic matter high. Soil acidity tends to increase and many soils appear to be marginally supplied with zinc and sometimes manganese and iron.

Soil is defined as a thin layer of earth's crust which serves as a natural medium for the growth of plants. Minerals, organic matter, water and air are some of the components of soil that help in the plant growth. A vertical section of the soil through all its horizons (layers) extends up to the parent material. The horizons in the soil profile vary in thickness and are identified by their morphological characteristics such as colour, texture, structure etc. Soil profile contains *Horizon A* – richer in organic matter and devoid of clay, iron or aluminium and rich in quartz; *Horizon B* – concentration of clay, iron, aluminium of humus alone or in combination; and *Horizon C* – is a layer of consolidated bed rock and its weathering. Soil profile studies (Fig. 4.1) reveal the surface and subsurface characteristics (texture, structure,

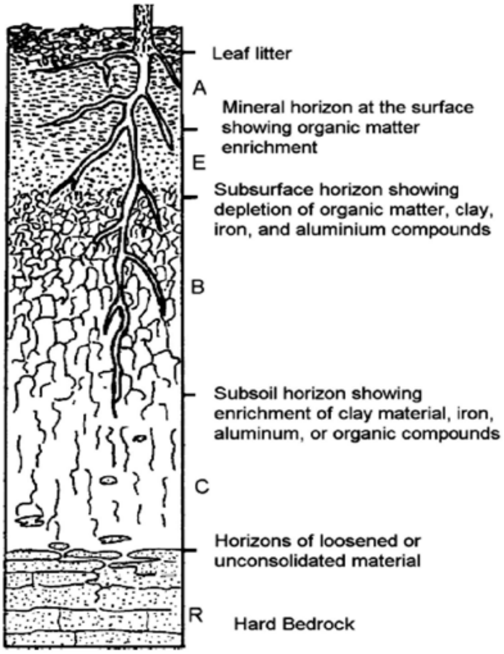


Fig. 4.1: Soil profile

drainage conditions and soil moisture conditions) that directly affect the plant growth. When soil horizons are present, they usually differ from one another in colour, texture, consistency, and structure. In addition, there are usually considerable differences in chemical characteristics or composition. The surface and subsurface are usually the coarsest layers.

The soil contains more organic matter than the other layers. It contains 45% mineral, 5% organic matter, 25% water and 25% air by volume. The O horizon is the topmost layer of most soils. It is composed mainly of plant litter at various levels of decomposition and humus. The B horizon is a mineral soil layer which is strongly influenced by illuviation. The C horizon is composed of weathered parent material. The texture of this material can be quite variable with particles ranging in size from clay to boulders. The C horizon has also not been significantly influenced by the pedogenic processes, translocation, and/or organic modification. The final layer in a typical soil profile is called the R horizon. This soil layer simply consists of unweathered bedrock. The major soil groups are: *Alluvial soil* is found in deltaic alluvium, calcareous alluvial soil etc. supporting largest share in agriculture. They are mostly light-sandy, red and yellow soil. *Black soils* vary in depth from shallow to deep. High degree of fertility with highly argillaceous, very fine grained sand is dark and contains high percentage of calcium and magnesium carbonates. Exceedingly sticky when it is wet and large and deep cracks form on contraction. It has low permeability and high values of hygroscopic co-efficient, pore space, maximum water holding capacity and true specific gravity. *Red soils* grade from poor thin gravelly and light coloured varieties on the plains and valleys. Soil is rather shallow, open in texture, deficient in organic matter and poor in plant nutrients. Lateritic soils are rich in nutrients and 10-20% of organic matter on higher elevations. Desert soil is covered under a mantle of blown sand which combined with the arid climate results in poor soil development (ICAR, 2005).

Texture, or the grain size composition of minerals that help make up a soil, is one of the most important properties of a soil. The irrigation requirement and management depends on soil and their properties such as: Texture, or the grain size composition of minerals that help make up a soil, is one of the most important properties of a soil because it is related to many other properties. Knowing the texture, of a soil gives an idea about its other properties. Soil texture can be grouped into: *coarse fragments* (gravels, stones, and boulders; greater than 2 mm in diameter), *sand* (the stuff beaches and dunes are mostly made of 2 mm to 0.05 mm in diameter), *silt* (one can't see the individual grains, the main component of dust and feels like flour; 0.05 mm to 0.002 mm in diameter), and *clay* (pure moist clay looks and feels like fresh axle grease and 30 to 40% clay in the soil will make it plastic like modeling clay; less than 0.002 mm in diameter). The loams and clay loams are generally good soils for irrigation because of its run-off, the number of irrigations necessary and the investment for drainage are low as compared with those in the case of other soils. The heavy soils often need surface as well as subsoil drainage. The light sandy soils involve a high application of costly inputs besides a considerable wastage of water. *Soil organic matter* holds over ten times more water than sand; a sandy soil with good organic content (around 4-5%) will hold more water. Over the time, clayey soils with good organic content may have an improved soil structure, supporting a deeper rooting depth.

Saturation refers to the situation when the soil's pore spaces are filled with water. With water replacing air in the large pore spaces, root functions temporarily stop (since roots require oxygen for water and nutrient up-take). Prolonged periods without root oxygen will cause most plants to wilt (due to a lack of water uptake), to show general symptoms of stress, to decline (due to a lack of root function and possible root dieback), and to die. *Field capacity* refers to the situation when excess water has been drained out due to gravitational pull. Air occupies the large pore spaces; and water coats the soil particles and organic matter, and fills the small pore spaces. A handful of soil at or above field capacity will glisten in the sunlight. In clayey and/ or compacted soils, the lack of large pore space slows or prohibits water movement down through the soil profile, keeping soils above field capacity and limiting plant growth. *Previous irrigation pattern* – Plants adjust rooting depth (to the extent that soil oxygen levels allow) to where soil water is available. Frequent irrigation eliminates the need for plants to develop a deep rooting system. A shallow rooting system makes the plant less resilient to hot, dry weather. Soil drainage is significantly worse in the plains and valleys with heavier soils and lower drainage density. The main determinants of soil drainage are the low slopes and heavier soils in the alluvium and colluvium clayey tracts, with little relation to soil depth and soil parent material. Soil particle size is one of the most important determinants of soil moisture retention, and is positively correlated to landforms.

Available water in soil is the amount of the water held in a soil between field capacity and the permanent wilting point. This represents the quantity of water "available" or usable by the plant. The amount of available water is low in a sandy soil. Loamy soils have the largest quantity of available water. In clayey soils, the amount of available water decreases slightly as capillary action holds the water so tightly that plants cannot extract it. *Permanent wilting point* refers to the situation when a plant wilts beyond recovery due to lack of water in the soil. At this point the soil feels dry to the touch. However, it still holds about half of its water; the plant just does not have the ability to extract it. Plants vary in their ability to extract water from the soil. For most plants, the *available water* is about 50% of the soil's total water supply before reaching the *permanent wilting point*. Onions are an example of a crop that can only extract about 40%. The plants have ability to survive on dry soil (drought mechanism) and many plants, like impatients, readily wilt as an internal water conservation measure. Some plants, like cacti, have an internal water storage supply and a waxy coating. Trees close the stomata in the leaves, shutting down photosynthesis, during water stress. Tall fescue is an example of plants that survive short-term dry soil conditions by rooting deeper (if soil conditions allow) reaching a larger water supply.

Soil texture	*Field capacity (FC)*	*Permanent wilting point (PWP) %*	*Bulk density g/cc (BD)*	*Available water (mm)/metre depth of soil profile. d = FC – PWP/100 × BD × soil depth*
Sandy	5 to 10	2 to 6	1.5 to 1.8	50 to 100
Sandy loam	10 to 18	4 to 10	1.4 to 1.6	90 to 160
Loam	18 to 25	8 to 14	1.3 to 1.5	140 to 220
Clay loam	24 to 32	11 to 16	1.3 to 1.4	170 to 250
Clay	32 to 40	15 to 22	1.2 to 1.4	200 to 280

Farms having soil with high *water holding capacity* (WHC) store more water and require less water for irrigation when compared with areas having soils with low WHC. In multiple soil layering, the farm's overall median year irrigation requirement uses area-weighted values of each soil's irrigation demand. Water holding capacity (WHC) of the soil is mainly influenced by texture. Sandy soil (greater than 80% sand) can hold 8 to 12% water, depending on the size of the sand particles. Any additional water would percolate out of the root zone or runs off the surface. A soil low in sand (less than 20%) can hold 18 to 20% water. Non-sandy soils allow plants more time between rainfall events or irrigations before they become stressed from lack of water (due to permeability).

Rooting depth is also another primary factor influencing irrigation management. Roots only grow where there are adequate levels of soil oxygen. In clayey or compacted soils, where a lack of large pore space restricts oxygen levels, roots will be shallow. Plants with a shallow rooting depth simply have a smaller profile of soil water to use. About 70 percent of a plant's roots are found in the upper half of the crop's maximum rooting depth. Deeper roots can extract moisture to keep the plant alive, but they do not extract sufficient water to maintain optimum growth. When adequate moisture is present, water uptake by the crop is about the same as its root distribution. Thus, about 70 percent of the water used by the crop comes from the upper half of the root zone. *Effective root depth* is that portion of the root zone where the crop extracts the majority of its water. Effective root depth is determined by both crop and soil properties and varies with plant species. The potential rooting depth is the maximum rooting depth of a crop when grown in a moist soil with no barriers or restrictions that inhibit root elongation. Potential rooting depths of most agricultural crops is 2 to 5 feet. *Length of Growing Period (LGP)* is defined as the period during the year when prevailing temperatures are conducive to crop growth (T mean ≥ 5°C) and precipitation and moisture stored in the soil profile exceed half the potential evapotranspiration (PET) (on a daily basis sufficient soil moisture should be accumulated in the soil profile to permit seed germination (model variable set to 50 mm)). The estimation of the growing period is based on a water balance model, which compares rainfall (P) with potential evapotranspiration (PET). If the growing period is not limited by temperature, the ratio of P/PET determines the start, end and type of growing period. The growing period starts when rainfall exceeds 50% of PET and ends with the utilization of the stored soil moisture after rainfall falls below PET. *Stage of growth* influences ET. Water needs increase as a plant grows in size during the season, and peaks during flowering and fruit development. Compared to the rooting system of a mature plant, newly planted or seeded crops don't have the root system to explore a large volume of soil for water. Recently planted and seeded crops will require frequent, light irrigations. In our dry climate, even "xeric" plants need regular irrigation to establish. *Water demand of a plant* varies greatly in the demand for water to (1) support growth, and (2) survive dry spells. These two are not necessarily related.

The FAO land suitability classification system has four different categories: Orders, Classes, Subclasses and Units. There are two orders (S and N) which reflect the kind of suitability: Suitable land (S) – Land on which sustained use for the defined purpose in the defined manner is expected to yield benefits that will justify required recurrent inputs without unacceptable risk to land resources. Unsuitable land (N) having characteristics which appear to preclude its sustained use for the defined purpose in the defined manner or which would create production, upkeep and/or conservation problems requiring a level of recurrent inputs unacceptable at the time of interpretation. The framework at its origin permits complete freedom in determining the number of classes within each order. However, it has been recommended to use only three classes within order S and two classes within order N. The class will be indicated by an Arabic number in sequence of decreasing suitability within the order and therefore reflects degrees of suitability within the orders: S1 – Suitable; S2 – Moderately suitable; S3 – Marginally suitable; N1 – Actually unsuitable but potentially suitable; and N2 – Actually and potentially unsuitable. Land capability classification of soil for agriculture purpose evaluates the soil characteristics, external land features and environmental factors. It helps in understanding the crop production potentiality and the probable damage of soil, deterioration in fertility etc.

Capability class	*Suitability*
I	Few limitations that restrict their use. Deep well-drained with water holding capacity. Suitable for intensive cropping
II	Limitation in choice of crop. Moderate conservation practice in preventing deterioration
III	Severe limitation in crop choice. Special conservation practices in raising of crops
IV	Very severe crop limitation and choice of crop. Cultivation once in 3 or 4 years
V	No erosion hazard. Severe limitation on wetness or overflow. Use of pasture of adaptable tree species
VI	Severe limitation to depth, slope, erosion hazard etc. Restricted to pasture and silviculture
VII	Totally unsuitable for crop cultivation. Use only for grazing
VIII	Very severe limitation. Unsuitable for agriculture/ silviculture. Only for recreation/wildlife.

The subclasses reflect kinds of limitations or main kinds of improvement measures required within classes. They are indicated in the symbol using lower case letters: c: Climatic conditions; t: Topographic limitations; w: Wetness limitations; n: Salinity (and/or alkalinity) limitations; f: Soil fertility limitations not readily to be corrected; and s: Physical soil limitations (influencing soil/water relationship and management). Land suitability units' grouping is used to identify land development units having minor differences in management requirements. This can indicate the relative importance of land development works. It is indicated by Arabic numerals, enclosed in parenthesis, following the subclass symbol. Sys and Verheye (1975) proposed the following capability index (Ci) based on nine parameters for crop production in the arid and semi-arid regions.

$$Ci = A.B.C.D.E.F.G.H.I.$$

where A = rating for soil texture (taken as 100 for best texture, say loam); B = rating for calcium carbonate (taken as fraction of 1 (one)); C = rating for gypsum (as above); D = rating for salinity (as above); E = rating for sodium saturation (as above); F = rating for drainage (as above); G = rating for soil depth (as above); H = rating for epipedon and weathering stage (as above); and I = rating for profile development (as above).

Sys (1975) proposed the following scheme for evaluating the degree of limitation ranging from 0 (suggesting no limitation and having Ci of 80 or more) to 4 (suggesting very severe limitation with Ci of 30 or less). No (0): The characteristics (quality) are optimal for plant growth (Ci 80 or more). Soil-Site Characteristics Related Land Quality Climate – Available moisture; *Topography and Landscape(t) – Resistance to erosion Wetness (w) conditions;* – Available moisture, – Drainage, – Flooding, Physical conditions of soil –

Texture; – Water availability – Gravels/Stoniness, – *Availability of foot-hold for (Surface and subsoil) root development* – Depth – Availability of foot-hold for plant growth – Calcium carbonate – Nutrient availability – Gypsum – Source of nutrient sulphur. Soil fertility (f) (Not readily correctable): Organic matter, – Cation Exchange Capacity (CEC), – Base Saturation, – Nutrient availability, Salinity and Alkalinity (n): Salinity – Groundwater depth and its quality – Alkalinity/Sodicity.

Agro-ecological Zone

An agro-ecological zone (AEZ) is a land resources mapping unit, defined in terms of climate, landform and soils, and/or land cover with a specific range of potentials and constraints with respect to land use. It refers to the division of an area of land into smaller units within a geographical continuum, which have similar characteristics related to land suitability, potential production and environmental impact. Soil type, climate (temperature, and rainfall and its variation), relevant meteorological characteristics, water demand and supply, including quality of water and aquifer conditions are the important parameters related to agriculture economy. Regionalisation methods emphasize the importance of physiographic divisions and administrative boundaries and not the water balance analysis, soil water retention capacity for crop potential, and land capability mapping/carrying capacity estimation. Moisture deficit regions were those where the length of growing period (LGP) was less than or equal to 180 days and 282 moisture deficit districts of India. The *thermal regime* is the other basic climatic parameter used to define the agro-ecological zones. The thermal regime refers to the amount of heat available for plant growth and development during the growing period. It is usually defined by the mean daily temperature during the growing period. In the regional and national AEZ assessments, thermal zones may be defined based on temperature intervals of 5°C or 2.5°C.

Rainfall and irrigation or soil moisture and irrigation are used in order to identify dry or drought prone areas and interventions.

GIA: Gross Irrigated Area, GSA: Gross Sown Area.
GIA/GSA = Irrigation Intensity.

Since irrigation is a major input, which modifies the soil moisture regime leading to changes in LGP, irrigation criteria were used to further redefine these regions. This criterion was used since the ultimate effect of dryness in an area is due to reduction in water availability for crop growth. Using the LGP and GIA/GSA, 177 dry land districts were identified. It was found that 42 per cent of the districts in India, covering a geographical area of 56 per cent, fell under the category of dry lands. Proportion of geographical area under forests; Average degree slope; Percentage area under forests from toposheets; Drainage density; Groundwater depth; Percentage slope; Soil drainage; Soil taxonomy; Bifurcation ratio of first and second order streams; Level of groundwater development – our estimate; Utilisable irrigation potential for development – our estimate; Seasonal rainfall intensity; Annual rainfall intensity; Seasonal rainfall average (1951-2001); Annual rainfall average (1951-2001); Frequency distribution of commencement of sowing rains (CSR) between June 15 and June 28; and Inter spell of more than eight days (Frequency of years with an inter spell gap of more than eight days is a very important sign of productivity to soil stress for crops), especially for paddy in unirrigated, upland situations could be used for AEZ.

4.2 Soil Water Irrigation

A plant extracts water from the soil with the hairs on the absorbing surface of their elongating roots, through osmosis and diffusion. On the surface of a leaf, there are numerous openings, stomata, through which water is lost in the form of vapour on account of the incident heat energy. The accumulated water vapour around the leaf tissues is further carried away by the wind into the atmosphere. The process of loss of water from the plants through the stomata and plant surface is known as *transpiration*. Water is pulled out as a continuous film from the root hairs to the leaf surface because of the sink strength of the atmosphere. Understanding of availability of soil water and irrigation options is essential in maintaining the crop growth. *Soil-moisture* is the amount of moisture present in the soil that is essential for deciding the time and the quantity of water to be applied. The moisture status in the root-zone can be estimated by inserting an iron probe or a tube. Resistance for forcing down the iron probe depends on the moisture content of the soil profile. In a wet soil, the probe will be forced down more rapidly and easily than in a dry soil. General overview of rainfall portioning in farming systems in semi-arid tropics of sub-Sahara Africa is shown in Fig. 4.2. Rainfall of 5.0 mm in one day should be regarded as useless since it will evaporate before infiltrating into the soil (Oliver, 1961). Days with less than 6.4 mm of rainfall or less than 0.003 m of runoff cannot supply effective moisture accumulation in soil and cause agriculture drought (Hershfiled et al., 1973). The temperature in the surroundings decreases due to insufficient amount of rainfall that cannot infiltrate into the soil but evaporate and crop consumption is thus reduced. In arid and semi-arid regions, drought's effect on crops may be reduced or eliminated by reserving enough water from available sources (Richer et al., 1961). Hence, winter rainfall is critical for maintaining soil moisture storage and groundwater recharge, as evaporation losses are low thus resulting in more recharge. In contrast a summer drought which is accompanied by high temperatures and high rates of evaporation has a more immediate impact on surface water resources. A drought in spring would result in inadequate reservoir filling and possible supply problems if followed by dry summer.

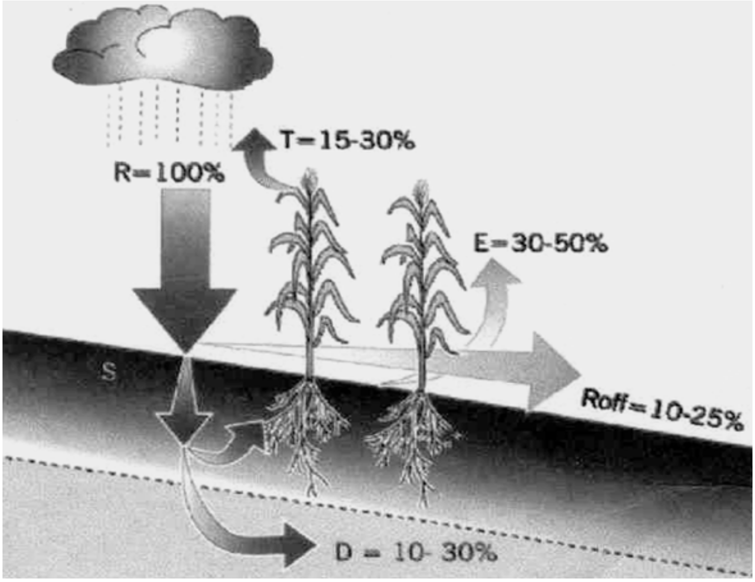


Fig. 4.2: Rainfall portioning in farming systems at semi-arid tropics of South Africa.
(**R** – Rainfall; **T** – Transpiration; **E** – Evaporation from interception and soil, **Roff** – Surface runoff; **S** – Soil Moisture; **D** – Deep percolation)

Evapotranspiration, ET is the rate at which a crop uses water for transpiration plus evaporation from the soil surface. Primary influences on ET include weather factors (solar radiation, temperature, wind, and humidity) and the stage of plant growth. On hot or windy days, ET will be higher; on cool, humid days, ET will be lower. *Stage of growth* influences ET. Water needs increase as a plant grows in size during the season, and peaks during flowering and fruit development. The total growing period is divided into growth stages: *Initial stage* is the period from sowing or transplanting until the crop covers about 10% of the ground. *Crop development stage* is the period that starts at the end of the initial stage and lasts until the full ground cover has been reached (ground cover 70-80%); it does not necessarily mean that the crop is at its maximum height. *Mid-season stage* period starts at the end of the crop development stage and lasts until maturity; it includes flowering and grain-setting. *Late season stage* is the period which starts at the end of the mid-season stage and lasts until the last day of the harvest; it includes ripening. Compared to the rooting system of a mature plant, newly planted or seeded crops don't have the root system to explore a large volume of soil for water. Recently planted and seeded crops will require frequent, light irrigations.

Water is supplied to the crops by way of rainfall, irrigation and combination of irrigation and rainfall. In some cases, part of the crop water need is supplied by the groundwater through capillary rise. In cases where all the water needed for optimal growth of the crop is provided by rainfall, irrigation is not required and the irrigation water need (IN) equals zero: IN = 0. In cases where there is no rainfall at all during the growing season, all water has to be supplied by irrigation. Consequently, the irrigation water need (IN) equals the crop water need (ET crop): IN = ET crop. In most cases, however, part of the crop water need is supplied by rainfall and the remaining part by irrigation. In such cases the irrigation water need (IN) is the difference between the crop water need (ET crop) and that part of the rainfall which is effectively used by the plants (Pe). In formula: IN = ET crop – Pe. (If sufficient rainfall, *then* no watering IN = 0; If no rainfall at all *then* IN = ET crop; If partly irrigation, partly rainfall then IN = ET crop – Pe. In other words, the effective rainfall is the total rainfall, minus runoff, minus evaporation and minus deep percolation; only the water retained in the root zone can be used by the plants, and represents what is called the effective part of the rainwater. The term effective rainfall is used to define this fraction of the total amount of rainwater useful for meeting the water need of the crops.

For the purpose of this text only two simple formulae are provided to estimate the fraction of the total rainfall which is used effectively. These formulae can be applied in areas with a maximum slope of 4-5%:

$$\text{Pe} = 0.8\ \text{P}\ 25 \text{ if P} > 75 \text{ mm/month};$$
$$\text{Pe} = 0.6\ \text{P}\ 10 \text{ if P} < 75 \text{ mm/month}$$

where P = rainfall or precipitation (mm/month); and Pe = effective rainfall or effective precipitation (mm/month).

In our dry climate, even "xeric" plants need regular irrigation to establish. *Water demand of a plant* vary greatly to (1) support growth, and (2) survive dry spells (note the two are not necessarily related). Figure 4.3 shows the crop growth stages and irrigation support requirement for normal productivity.

An example of crop-weather calendar issued by the Indian Meteorological Department for individual crops and geographical location is shown in Fig. 4.4. The period of sowing vary within a village due to resource availability (including labour). Crop growth phases also vary from agriculture plot to plot and their water demand and vulnerability to weather. The critical water demand from rainfall or stored supply system is extended over an extended period (Fig. 4.5). Drought and dry spells were used in the long-term rainfall

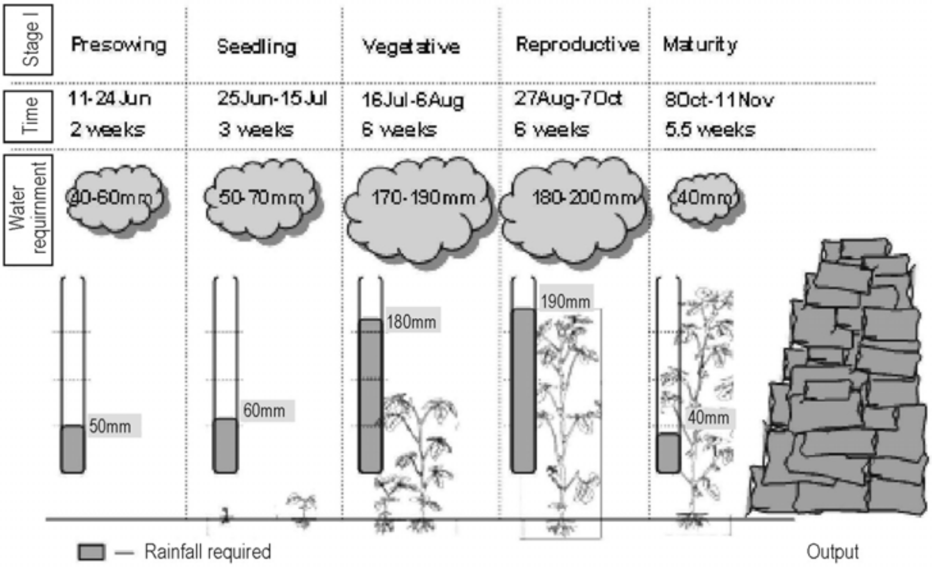


Fig. 4.3: Crop calendar and rainfall pattern.

analysis to determine probabilities of occurrence of each category. *Drought*: Meteorological drought, defined as cumulative average season rainfall. *Severe dry spell:* A dry spell of more than 15 days occurs between 61 and 90 DAS (Days After Sowing), during flowering and grain filling, requiring 3–4 SI applications. *Mild dry spell:* A dry spell of less than 15 days appear between 61 and 90 DAS requiring 2-3 SI applications. Furthermore, there are more than average dry days between 0-30 DAS and 31-60 DAS. *No dry spell:* Less than average dry days in any given growth period through 0-90 DAS.

There are different types of water limitations adversely affecting crop production. Meteorological droughts, occurring on an average one to two years out of ten in the Sahel (Sivakumar and Wallace, 1991), can be defined as when cumulative rainfall is insufficient to support a crop. Dry spells are prolonged periods (ranging from one week to several weeks) between rain events within the season. The impact of dry spells on final yield depends on which crop development stage that is affected. Many local farming practices in semi-arids attempt to overcome dry spell occurrences through in situ water harvesting (WH) techniques such as Zai pitting, stone bunds, terracing, and mulching. The estimated dry spell impact of a crop benefiting from Supplementary Irrigation (SI) is based on the capacity of the system to bridge dry spells as they occur, with only two SI application volumes stored in the reservoir (after which the reservoir needs to be replenished by a rain). Robust and rainfall independent off-farm livelihood opportunities need to be targeted in the drought mitigation strategy.

Crop Weather Calendar

State : Maharashtra
Districts: Ahmednagar, Nanded, Beed Pune

Crop: Jowar (Rabi)
Irrigated/Non-irrigated

Variety: M-35-1, SPV 86 Soil: Medium black
Duration: 110-120 days

Weather warnings	Rain	100 mm / Day							> 150 mm / day												> 150 mm / day														
	Duration of wet spell	10 mm for 20 Days							> 50 mm for 20 days												> 70mm for 26 days														
	Cloudy weather	Cloudy weather																																	
	Drought	8 Days							30 Days												30 Days														
	High winds																																		
	Temperature	MA							MA												MA														
	Hailstorm	Hail storm							Hail storm												Hail storm														
Weather conditions favorable for incidence of pests & disease	Pests	Aphids, Stem borer, Shoot fly, Army warm, Midge fly							Aphids, Stem borer, Shoot fly, Army warm, Midge fly												Aphids, Stem borer, Shoot fly, Army warm, Midge fly														
	Weather	Cloudy and humid weather							Cloudy and humid weather												Cloudy and humid weather														
	Diseases	Downey Mildew							SMU												Rust														
	Weather	Cloudiness							Cloudiness												Cloudiness														
Normal of phase wise Water requirement									45.1					60.4			99.4				51.7			38.9											
Weekly normal weather	Total rainfall (mm)			24.7	30.2	36.4	50.6	47.6	24.9	17.8	7.4	13.2	6.5	7.6	2.9	3.1	2.9	0.4	1.2	0.4	1.9	0.4	0.2	1.5	0.2	0.5	0.9	1.0	1.1	0.4	1.3	1.2			
	Max Temp. 0⁰C			29.8	29.9	30.8	31.6	31.5	31.9	32.7	32.7	32.0	31.4	30.9	30.7	30.2	29.5	29.6	29.4	29.6	29.2	29.8	30	30.4	31.0	31.7	32.3	32.8	33.6	34.5	35.4	36.6			
	Min Temp 0⁰C			21.4	21.1	21.0	21.3	21.1	20.8	19.8	18.6	18.0	17.1	15.9	15.1	13.9	13.3	12.8	12.0	11.8	11.8	11.9	12.3	12.3	13.0	13.1	13.3	1402	15.1	15.8	16.8	17.6			
	Sunshine hrs			5.0	5.1	6.6	6.6	6.7	7.7	8.5	9.1	9.3	9.2	9.4	9.4	9.3	9.6	9.4	9.6	9.6	9.6	9.2	9.9	9.9	10.2	10.2	10.5	10.3	10.3	10.2	10.1	10.1			
Life history & mean dates of important epoch crop growth																					Maturity & Harvesting														
																			Grain Formation																
															Flowering																				
									Vegetative Growth																										
					Germination																														
			Sowing																																
Standard week		33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	1	2	3	4	5	7	6	7	8	9	10	11	12	13

Fig. 4.4: Crop weather calendar.

Source: Indian Meteorological Department

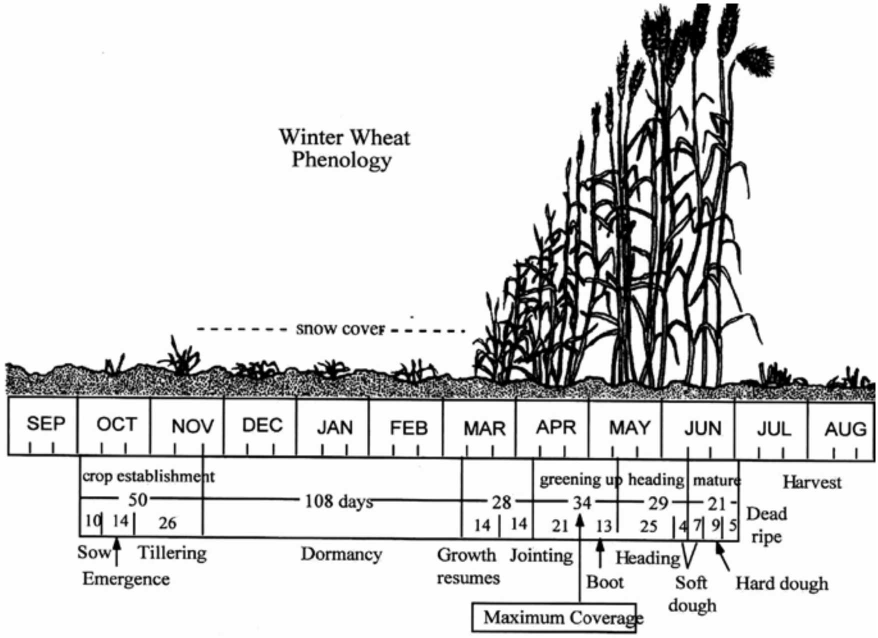


Fig. 4.5: Weekly crop water demand at various stages of growth

The probability of drought is 0.1 and cannot be mitigated since there is insufficient amount of water available for harvesting and hence for SI. Seventy-five per cent of the severe dry spells can be partly mitigated with water harvesteng. SI, but not fully as they occur late in the rainy season (during flowering and grain filling) and require a minimum of three SI applications. As the water harvesting system can only support two SI applications, the dry spell is only partly mitigated, transforming the severe dry spell to mild dry spells. Field experience indicates that all of the mild dry spells can be mitigated.

4.3 Crop Growth

People grow crops in their lands for survival, irrespective of conducive parameters based mainly on their previous knowledge of geography, climate, soil and water. They have changed their crop type and management practices. A summary of the crops that are grown commonly either in the humid or semi-arid or arid conditions with required supplementary irrigation is listed below. *Fodders* require frequent irrigations for maximum growth. The optimum moisture range is from field capacity to about 75% of the availability. Berseem requires 800 mm during eight months of its growth. It needs irrigations of about 20 days interval during December to January and 15 days during November, February and March, and 10 days interval during

September, October and April. Lucerne needs about 1800 to 2000 mm of water during the first year of growth. If the soil moisture is allowed to fall below 75% of availability the yield reduction in berseem, lucerne, cowpeas, sorghum and cluster-bean (guara) will be 30, 15, 15, 10 and 5 per cent, respectively. Hence, depending upon the availability of water, suitable forage crops can be selected for a given locality.

Vegetables – Most of the vegetable crops are of short duration and grow quickly and need frequent irrigation leading to 70 to 80% of soil moisture in the maximum root-zone. Potato grown on sandy-loam soil needs 500 mm of water during its growth, at intervals of 10 to 12 days or 8 to10 days. Adequate water-supply should be ensured during stolonization and tuber formation stages (20-60 days). Onion and garlic are shallow-rooted crops and need very frequent irrigation. Bulbing is the most critical stage from the point of view of applying water. About three weeks before maturity, the irrigation is delayed to enhance the keeping quality of the bulbs. Tomato grown in India throughout the year requires irrigation at intervals of 10 to 12 days during the summer and of those of 15 to 20 days during the winter. Excessive irrigation, during ripening results in fruit-cracking. Cabbage, cauliflower and knol-knol require optimum moisture regime from 100 to 50 per cent of availability. Radish, turnip, beet-root and other leafy vegetables need frequent irrigation to maintain the range 100 to 75 per cent of availability in the top 30 cm of the soil. *Water-melon and musk-melon* are grown during the summer and need water at intervals of 8 to 10 days. Excessive irrigation should be avoided during the ripening stage. In other crops of the cucubitaceae family, such as pumpkin, bottle-gourd, ridge-gourd, sponge-gourd, and cucumber irrigation should be applied at intervals of 10 to 12 days during the summer. The maximum root-zone of these crops lies between 40 and 60 cm in the soil profile.

Spices and condiments crops are turmeric, ginger, chillies, ajwan, cumin and coriander. Irrigation for turmeric and ginger should be maintained at 100 to 70 per cent of available moisture in the maximum root-zone, i.e. the top 50 cm of the soil. For chillies, 100 to 50 per cent of available soil moisture in the active root-zone extending to about 60 cm in the soil should be maintained. Coriander, cumin and ajwain are winter crops and need irrigation at intervals of 10 to 12 days on light soils and 15 to 20 days on heavy soils. The water requirements during their period of growth are around 500 to 600 mm. *Fruit-trees* are deciduous trees that shed their leaves during the winter and remain dormant for 3 to 4 months. The evergreen trees include citrus, mango, banana, chikoo, pineapple, papaya, date-palm, etc. They require adequate soil moisture of 100 to 75 per cent of availability during their establishment period of 3 to 4 years. After the full development of the root-zone down to 75 to 90 cm, the crops may be irrigated when two-thirds of the available moisture is depleted during blossoming, fruit-setting and fruit enlargement. At other periods and during dormancy in the case of deciduous trees, irrigations may be applied when soil moisture almost reaches the wilting point. Papaya and banana are shallow-rooted and short-lived species. They need to be irrigated when the available moisture in the top 30 cm of the soil layer is depleted to 80 per cent of availability. This will necessitate irrigation at intervals of 8 to 10 days during the rainless period in the tropical climate. The date-palm can withstand high temperatures and low humidity but needs regular irrigation during flowering and fruiting to produce good yields. In case of grapes too much moisture during the ripening causes the splitting and rotting of the berries. A slight stress during this period results in increased sucrose content and better colour. It is profitable to irrigate coffee after the cessation of the monsoon rains during flowering to avoid flower-shedding. Sprinkler irrigation practice during the post-monsoon period has doubled the crop yield of coffee successfully.

Important kharif legumes are cowpeas, green-gram (mung), black grain (mash), kidney-bean, and pigeon-pea. The crops are generally grown under rain-fed conditions and rarely receive irrigation because of their deep root-systems. When grown alone, one or two irrigation would be beneficial to boost their yields and income on account of their high market price and protein. Winter grain legumes i.e. grain, lentil, pea, and Indian bean (*Dolichos lablab*) are irrigated two or three times during their growth. Critical periods in the life-span of the legumes are early vegetative growth, flowering and pod development. Grain legumes are extremely sensitive to excess moisture wherever there is a likelihood of the soil becoming saturated for a prolonged period as a result of continuous and heavy rains. Pigeon-pea and gram are very hardy and can deplete soil moisture up to 1.5 to 2 metres deep and are suited to water-scarcity areas. Principal oilseeds such as groundnut, sesamum and niger during kharif and safflower, mustard, castor and linseed during rabi are grown under rain-fed conditions. During kharif they often suffer a setback during their growth owing to ill-distributed rainfall. Maintaining moisture in the range of 100 to 50 per cent availability by one or two supplementary irrigation increases their yield. Safflower and mustard are relatively hardy crops and can stand more unfavourable conditions than others. Groundnut is also grown during the winter on red and laterite soils and needs 8 to 10 irrigations of 50 mm each applied at 10 to 15-day intervals during the growth period. Safflower, mustard and lineseed are grown alone or mixed with wheat or other cereals and receive 3 or 4 irrigations during their growth.

Cotton is grown in India (April to October) depending upon the species and varieties, soil types and the distribution of rainfall. It is a deep-rooted crop, extremely sensitive to excess moisture and lack of aeration. The optimum range of soil moisture for the crop is from the field capacity to 20 per cent of availability in 0 to 75 cm of the root-zone. It is very sensitive to excess moisture and should be grown on ridges in humid regions. On heavier soils it is preferable to maintain better aeration. Jute needs continuously moist soils for the rapid elongation of the stem, the strands of which are used as fiber. The optimum moisture regime is from the capacity to 70 per cent of availability in the maximum root-zone of the crops which extends to about 45 cm of soil's depth. Tobacco is grown on heavy soils under rain-fed conditions for bidi-making and the optimum moisture regimes are from the field capacity to 70, 60, and 50 per cent of the availability. Cigar tobacco for cigar needs light and frequent irrigation during four months; and for hookah tobacco 12 to 13 irrigations of 50 mm of water each are required.

Sugarcane crop is grown under irrigation for 10 to 18 months. The optimum soil moisture for sugarcane has been found to be 100 to 50 per cent range of availability in the maximum root-zone, extending up to 50 to 75 cm in depth. The crop should never suffer from moisture stress during its growth as it affects growth rate and cane yield. The levels of water requirement in different parts of India are: 1400 to 1500 mm (Bihar); 1600 to 1700 mm (Andhra Pradesh); 1700 to 1800 mm (Punjab); 2200 to 2400 mm (Karnataka); 2000 to 2300 mm (Madhya Pradesh); and 2800 to 3000 mm/year (Maharashtra). Rice is grown in lowland and upland conditions and throughout the year in some parts of the country. Under lowland conditions, the rice crop is generally transplanted in the puddled soil. The practice of keeping the soil saturated or up to shallow submergence of about 5 cm throughout the growing period has been found to be the most beneficial practice for obtaining maximum yields for lowland rice. When water resources are limited, the land may be submerged at least during the critical stages of growth, viz. tillering and flowering, and maintained only saturated at other stages, thus economizing on water without seriously decreasing the yields.

When the weather is humid and evapo-transpiration rates are low and also when the water-table is near the surface, even maintaining the soil moisture near saturation is adequate and when weather is hot and arid, the practice of submerging the land is found to be more advantageous than when the soil is kept only saturated. When continuous submergence is practiced it is necessary to drain the soil two or three times during the period of growth, especially on poorly drained clayey soil. The drainage period should last from 4 to 8 days, depending upon the type of the soil. Total water need for rice under different conditions are: 1000 to 1500 mm (heavy soils, high water-table, the presence of hard pan in the subsoil, short duration varieties, kharif season); 1500 to 2000 mm (medium soils, kharif or early spring season) and 2000 to 2500 mm (light soil, long-duration varieties of rice grown during kharif or medium-duration varieties grown during summer, deep water-table). Special varieties, known as 'deep-water-rice' or 'floating-rice', are also available. They grow very tall and rapidly and can stand submergence up to three metres of water.

Wheat is grown during the rabi season in the country, when the amount of rainfall is low and it is necessary to irrigate the crop for exploiting its yield potential. The optimum soil-moisture range for tall wheat is from the field capacity to 50 per cent of availability. The dwarf wheat needs more wetness and the optimum moisture range is from 100 to 60 per cent of availability. The active root-zone of the crop varies from 50 to 75 cm, depending upon the soil type. The critical stages during the growth are crown-root initiation (three weeks after sowing), flowering and grain development. Moisture stress at each of these stages can erode the yield by about 25 per cent. Wheat is grown after the pre-sowing irrigation (rauni) when there is no adequate moisture at the time of sowing. *Barley* is similar to wheat in its growth habits, but can withstand more droughts because of its deeper and well-proliferated root-system; the active root-zone of barley extends to 60 to 75 cm on different soil types. The optimum soil moisture ranges from the field capacity to 40 per cent of availability. About two irrigations are adequate in the northern parts of the country on sandy-loam soils.

Maize needs the optimum soil-moisture range from 100 to 60 per cent of availability in the maximum root-zone which extends from 40 to 60 cm on different soil types. The critical stages of growth are the early vegetative period (30 to 40 days after sowing) and tasselling (45 to 50 days). Moisture stress for a week during the early vegetative stage can reduce the yield by 25% and during tasselling to the extent of 50%. The actual irrigation requirement of the crop varies with the amount of rainfall. In the northern parts of India, 2 or 3 irrigations (100 to 150 mm of water) are required to establish the crop before the onset of the monsoon. Afterwards, the irrigations are applied only if soil moisture falls below the optimum owing to long dry spells. It is very sensitive to excess water and the submergence of the soil for three to four days during the vegetative or flowering period can reduce the yields up to 50 per cent. At Arbhavi (Karnataka), three irrigations are found adequate during kharif, whereas five irrigations of 330 mm of water are necessary during rabi to obtain the maximum yield. Two, 11 and 18 irrigations are necessary to raise the crop during kharif, rabi and the hot-weather seasons respectively, the amount being 100, 550, and 900 mm during these seasons at Bhubaneshwar (Orissa). Four irrigations (500 mm of water) are required for growing maize during kharif at Udaipur (Rajasthan).

Sorghum and other millets are the hardiest among the cereals that are grown during kharif under rain-fed condition. The optimum moisture range is from the field capacity to 40 per cent of the availability. The sorghum roots can extend down to 100 to 150 cm, but the other millets, such as pearl-millet, crow-foot millet and Italian millet, have shallow root systems, extending 30 to 45 cm in the soil profile. Pre-flowering and grain development are the two critical stages in respect of moisture. Wherever the facility exists, the crop should be irrigated at least at the critical stages to maintain optimum moisture in the root-zone during the dry spells.

The seasonal flowering plants grown in lawns and gardens need to be irrigated very frequently to maintain the surface 30-cm layer moist at irrigation intervals of 5 to 8 days, depending upon the severity of the climate. A lawn may be irrigated at intervals of 10 to 12 days in summer and at those of 15 to 20 days during the winter to maintain its fresh and green growth. The interval between two irrigations depends primarily on the rate of soil-moisture depletion. Normally, a crop has to be irrigated before soil moisture is depleted below 50 per cent of its availability in the root-zone. The intervals are shorter during the summer than in winter. Similarly, the intervals are shorter in the case of sandy soils than in the case of heavy soil. When the water supply is very limited, the intervals are prolonged. The crops are then irrigated only at critical stages.

4.4 Crop-water

The crop-water requirement is influenced by: *Influence of climate* – A certain crop grown in a sunny and hot climate needs more water per day than the same crop grown in a cloudy and cooler climate. There are, however, apart from sunshine and temperature, other climatic factors which influence the crop-water need. These factors are humidity and wind speed. When it is dry, the crop-water needs are higher than when it is humid. In windy climates, the crops will use more water than in calm climates. The highest crop-water needs are thus found in areas which are hot, dry, windy and sunny. The lowest values are found when it is cool, humid and cloudy with little or no wind. Hence, it is clear that the crop grown in different climatic zones will have different water needs. *Crop type* has an influence on the daily water needs of a fully grown crop; i.e. the peak daily water needs of a fully developed maize crop will need more water per day than a fully developed crop of onions. The crop type also has an influence on the duration of the total growing season of the crop.

There are short duration crops, e.g. peas, with duration of the total growing season of 90-100 days and long duration crops, e.g. melons, with duration of the total growing season of 120-160 days. There are, of course, also perennial crops that are in the field for many years, such as fruit trees. Crops differ in their *response to moisture deficit.* This characteristic is commonly termed “drought resistance”. When crop-water requirements are not met, crops with high drought sensitivity suffer greater reductions in yields than crops with a low sensitivity. Group one – low sensitivity (ground nuts, safflower); Group two – low sensitivity (sorghum, cotton, sunflower); Group three – low sensitivity (beans) and Group four – high sensitivity (maize). In agriculture, *water use efficiency* is defined by crop yield produced per amount of water used, measured in dry matter yield (kg ha^{-1}) and transpiration (m^3 ha^{-1}) respectively. However, when discussing water efficiency of different crops one also has to consider the food value of the crop.

Growth period and crop water requirement is summarized selectively in Table 4.1. It includes the amount of water for meeting the needs of evaporation, transpiration and metabolic activities (all together known as consumptive use), losses during the application of irrigation water and water needed for special operations, such as land preparation, transplanting, the leaching of excess water, etc. The consumptive use depends upon the weather, the type of crop canopy, the soil moisture status and the stage of the crop. The application losses depend upon the type of the irrigation system, the soil texture and structure, and management practices. The special needs depend upon such factors as the moisture status of the soil as well as water, and the nature of the crop species grown. The consumptive needs of water by a crop cannot be reduced and no moisture economy is possible in the case of this item on a field scale, if the aim is to obtain the maximum yields.

Once the total growing period is known, the duration (in days) of the various growth stages has to be determined. *Initial stage* is the period from sowing or transplanting until the crop covers about 10% of the ground. *Crop development stage* starts at the end of the initial stage and lasts until the full groundcover has been reached (groundcover 70-80%); it does not necessarily mean that the crop is at its maximum height. *Mid-season stage* starts at the end of the crop development stage and lasts until maturity; it includes flowering and grain-setting. *Late season stage* start at the end of the mid-season stage and lasts until the last day of the harvest; it includes ripening.

4.5 Crop Irrigation

The net quantity of water to be applied depends on the moisture deficit at the time of irrigation in the root-zone. The depth of irrigation applied is greater when irrigations are given at longer intervals. Similarly, the finer is the soil texture, the greater is the amount of irrigation applied on account of the higher water-holding capacity of the soil. The deficit (*d*) is estimated from the field capacity (FC), the actual soil moisture content at a given time (Mc), the bulk density of the soil (Bd) and the depth of the root-zone (D) of the crops in question by the relationship.

$$d = \mathrm{FC} - \mathrm{Mc}/100 \times \mathrm{Bd} \times \mathrm{D}$$

In a canal supply system of irrigation the quantity of water to be released (once in 10 or 15 days) from the storage system needs to be ascertained for planning purposes. The rate of flow of water at a point in a straight ditch or

Table 4.1: Total crop growing period, water need and their sensitivity to drought (FAO, 1979)

Crop	*Total growing period (days)*	*Crop water need (mm/total growing period)*	*Sensitivity to drought*
Alfalfa	100-365	800-1600	low-medium
Banana	300-365	1200-2200	high
Barley/Oats/Wheat	120-150	450-650	low-medium
Bean green	75-90	300-500	medium-high
Bean dry	95-110	350-500	medium-high
Cabbage	120-140		
Carrot	100-150		
Citrus	240-365	900-1200	low-medium
Cotton	180-195	700-1300	low
Cucumber	105-130		
Eggplant	130-140		
Flax	150-220		
Grain/small	150-165		
Lentil	150-170		
Lettuce	75-140		
Maize sweet	80-110		
Maize grain	125-180	500-800	medium-high
Melon	120-160	400-600	medium-high
Millet	105-140		
Onion green	70-95		
Onion dry	150-210	350-550	medium-high
Peanut/Groundnut	130-140	500-700	low-medium
Pea	90-100	350-500	medium-high
Pepper	120-210	600-900	medium-high
Potato	105-145	500-700	high
Radish	35-45		
Rice	90-150	450-700	high
Sorghum	120-130	450-650	low
Soybean	135-150	450-700	low-medium
Spinach	60-100		
Squash	95-120		
Sugarbeet	160-230	550-750	low-medium
Sugarcane	270-365	1500-2500	high
Sunflower	125-130	600-1000	low-medium
Tobacco	130-160		
Tomato	135-180	400-800	medium-high

Note: Growing period and water needs may vary with hybrid and normal variety of crops. It is recommended that information may be obtained from the local Agriculture office. The details are used in the crop-water demand and planning purposes only.

in an open channel can also be determined by multiplying the cross-sectional area of water at that point by the average velocity. Under field conditions, it is impossible to maintain a uniform cross-section and, thus, a uniform velocity at various points. The values of irrigation needs during this period are worked out by subtracting the values of effective rainfall, ground-water and dew from the total water needs. These periodic values, when totalled for the entire period, furnish the total irrigation needs in a locality after making the correction for irrigation efficiency.

Total irrigation needs = Total water needs + contribution from rainfall
dew and groundwater × Irrigation efficiency

The precise knowledge on the quantities of irrigation water not only ensures a high efficiency of water use by the crops but also reduces nutrient losses through leaching and results in better aeration of the soil. Irrigation water is measured under two conditions, viz. at rest and in motion. The units commonly used for expressing the volume of water at rest are litres, cubic metres, hectare metres, etc. The rate of flow is expressed in terms of units of volume per unit of time, e.g. litres per second, cubic metres per minute, hectare metres per day, etc.

The calculation of *consumptive water use* in irrigation (or net irrigation water requirements) is carried out in monthly time steps and can be presented in statistical tables or maps at different levels of spatial aggregation. Consumptive use of water in irrigated agriculture is defined as the water required in addition to water from precipitation (soil moisture) for optimal plant growth during the growing season. Optimal plant growth occurs when actual evapotranspiration of a crop is equal to its potential evapotranspiration. Potential evapotranspiration of irrigated agriculture is calculated by converting data of irrigated area by crop. The water requirements of specific crops are calculated as a percentage of the PET. This "percentage" is called the *crop coefficient* (Kc). Crop coefficients depend on the type of crop and its stage of growth. *Efficiency of field irrigation* is determined by measuring the quantity of irrigation water applied and stored in the root-zone. If it is not possible to measure the efficiency, the following broad values are suggested as a guide for surface-irrigation methods. Irrigation efficiency (%) of the field is dominated by soil class and is grouped as: 60% (sandy), 65% (sandy loam), 70% (sandy loam), 75% (clay loam) and 80% (heavy clay). *Depth of irrigation* is the quantity of water needed for net irrigation on different soil types per metre depth of soil profile at 50 per cent of soil-moisture availability: Sandy (25 to 50 mm irrigation depth); Sandy loam (45 to 80 mm); Sandy clayey loam (70 to 110 mm); Clay loam (80 to 120 mm); and Heavy clay (100 to 140 mm). The depth of the soil to be wetted by irrigation depends upon the extent of the root-system of different crops. In the case of annual crops, the root-system is a dynamic one, growing to its full depth till about the flowering stage. When rains are anticipated, it is better to under-irrigate the field crop to accommodate the rainfall and reduce the amount of irrigation water to be applied.

To calculate the water requirements of a crop, we multiply the PET times the crop coefficient using the following equation:

$$\text{PET} \times \text{Kc} = \text{crop water requirements} \tag{1}$$

where PET is the sum of daily PET over the time period of interest, such as the 3-day total, the weekly total, etc. and Kc is the crop coefficient corresponding to the current stage of crop growth.

Adjust for irrigation system efficiency,

$$\text{PET} \times \text{Kc} \div \text{Eff} = \text{irrigation water requirements} \tag{2}$$

where Eff is the overall efficiency of the irrigation system.

The rate of evapotranspiration coming from the irrigated area per month and per grid cell is calculated by multiplying the area equipped for irrigation with cropping intensity and evapotranspiration for each crop.

$$\text{ET} = \text{IA} \times \Sigma\text{c}(\text{CIc} \times \text{Kc} \times \text{ETo})$$

where ET is the actual evapotranspiration of an irrigated grid cell for a given month; IA is the irrigated area in percentage of cell area for the given grid cell; c is a crop under irrigation; Σc is the sum over the different crops; CIc is the cropping intensity for crop c; Kc is the crop coefficient, varying for each crop and each growth stage and ETo is the reference evapotranspiration. The difference between the calculated evapotranspiration of the irrigated area and actual evapotranspiration under non-irrigated conditions is equal to the consumptive use of water in irrigated agriculture in the grid cell, i.e the net irrigation water requirement. In the case of paddy rice, an additional amount of water is needed for flooding. It is computed by multiplying the area under irrigated rice by a water layer of 25 cm.

4.6 Water Use Efficiency

Crops differ in their response to moisture deficit and it is commonly termed “drought resistance”. When crop-water requirements are not met, crops with high drought sensitivity suffer greater reductions in yields than crops with a low sensitivity. However, when discussing water efficiency of different crops one also has to consider the food value of the crop. In times of drought, agriculture productivity declines significantly. A period of only a few weeks without precipitation may cause serious problems for the farmer. In arid and semi-arid regions, drought’s effect on crops may be reduced or eliminated by reserving enough water from available sources. It is important to know drought durations in growing season in terms of scheduling irrigation, operation and management of agriculture production and information about how surface and subsurface water supplies, that answers to water demand of a crop in drought periods, should be operated. Drought intensity and duration must always be related to a calendar of crop sensitivity to rainfall. Assessing drought severity requires a measure of effective rainfall in relation to soil moisture and plant condition, rather than just summing rainfall deficiencies (Wilhite and Glantz, 1985). Agriculture drought is specifically concerned with cultivated plants, as opposed to natural vegetation. Agriculture drought is characterized by estimated water demand and expected water supply (Rawls et al., 1993). They are dependent on agro-climatic and economic conditions. It is adequate to consider and place emphasis on a single crop grown homogenously over the major area of the region. The water supply in arid and semiarid area is mainly from seasonal random precipitation (Kumar and Panu, 1997).

4.7 Water Stress Situation of Crops

The year-to-year variation in total rainfall, its monthly and daily distribution characterize the water-limited environments and generate a wide diversity of climatic scenarios. Owing to this, possible water stress patterns are: intermittent, when stress can occur at any time and with varying intensities between emergence and maturity; alternating with periods of plant recovery; and terminal (low rainfall area), where the crop grows and matures on a progressively depleted soil moisture profile. In the presence of water stress situation and with the uncertainty on drought occurrence (predictable or not), the type of drought (intensity, period) governs the optimal crop management schemes. Depending on the information (warning networks, field indicators) and resource availability (irrigation), the farmers may have opportunities to revise its initial cropping strategy at given periods of the growing season (Debaeke and Aboudrare, 2004). Evidences show that in the situation of acute water deficit caused by a major drought, farmers often “rationalize” the use of available water by reducing an area under water-intensive crops in favour of less water intensive crops. This is however practiced as a temporary measure with the area of rice typically restored once the drought is over.

Indian agriculture mainly depends on the *monsoon rains* and farmers anxiously await the onset of the monsoon and a favourable distribution of rainfall during the rainy season. As there is a considerable variation from year to year in the advent of the monsoon over climatic divisions, the predicting of the dates of its onset and giving advance indications to the probable distribution of rainfall are of great economic significance. Delays in the *timely onset of rains and breaks in the rainy spells* during the cropping season are the two great problems which the Indian farmer has to confront with, especially those in the dry farming tract. During the monsoon season, in some years, over certain regions the rains abruptly cease. Although clouds persist in those areas, their vertical extent is not large enough to precipitate. On such occasions, the clouds can be made to grow and shed their moisture as rain through appropriate seeding. Between the monsoon seasons, the extreme weather parameters turns into extreme conditions due to global circulation system resulting into events/conditions that affect the growth potential of crops at the field level. Some of the conditions are listed. *Thunder-storms* associated with rain or hail is experienced before and after the monsoon season and when sufficient moisture is not present in the air. *Dust-storms* occur over north-west India. The frequency of hail-storms is small in winter, but increases generally as the season advances to summer. It is difficult to forestall a hail-storm, since its occurrence is sporadic and confined to very limited areas; a thunder-storm also in itself is a highly localized phenomenon. *Western disturbances* are followed by cold waves over northern and central India and these cold waves are injurious to vegetable and fruit crops. Irrigation or spraying with water helps to mitigate *frost damage* in the fields. The use of heaters in orchards will help to raise the temperatures by as much as 50°C. Valleys in which cold air stagnates are subject to frost to a greater extent. Trees planted as shelter belts or as shade-trees protect the crops during the periods of mild frost. When the standard screen temperature is 5-70°C, some plant injury is possible even if the stage of ground frost is not reached. Valuable crops can also be protected by covering the ground with suitable material, e.g. paper, plastic or celophane, to reduce the cooling of the ground through radiation.

The *air temperature* is a decisive factor in plant growth, especially in the subtropics. The growing season in these latitudes, where frost conditions set a limit, is defined on the basis of air temperature. High temperatures are also of special importance, as they may have damaging effects on crops during the periods of water stress in the arid or semi-arid regions. Each crop is known to have its own optimum, maximum and minimum temperature conditions. Air temperatures bear a close relationship with the incoming solar radiation and the energy available for the growth of plants. The maximum temperatures in the country are high in March, April and May over northern Deccan and central parts of India. Later in June and July, the highest values shift northwards and north-westwards. In July and August, Tamil Nadu also experiences high maximum temperatures. The cold season begins over India by early December. Night air temperatures fall rapidly by 7-8°C below the normal and sometimes more in regions north of the Deccan Plateau and by about 5°C in the peninsular parts of the country due to influence of western disturbances, which are followed by cold dry northerly winds. The ground temperatures are usually much lower than air temperatures. The crops may be subject to sub-zero temperatures and damage due to chilling or ground frost is likely to take place. The frost hazard is greatest in northern Punjab, being 10-20 days each in December, January and February. Southwards and eastwards of this area, frost occurrence decreases rapidly. *Sunshine* is not a limiting factor anywhere in India. Even during the monsoon, it is not the lack of sunshine but excessive rain that is responsible for an occasional set-back to plant growth. Continued cloudiness during flowering is injurious to all plants. It also creates conditions favourable to the multiplication of pests and diseases. High humidity and warm temperatures are conducive to most plant diseases. *High winds or squalls* are experienced in association with cyclones, depressions and dust-storms and thunder-storms. It may cause mechanical damage to crops, such as breaking or lodging. Light winds blowing from colder parts will bring about a drop in temperature and create frosty conditions. Warm and dry winds cause greater losses through evaporation and result in water stress. Windbreaks planted across the prevailing wind directions afford protection to the plants against damage owing to winds. They are recommended as a useful means to reduce the evapotranspiration losses, frost damage and soil erosion by wind.

In large parts of the country where *rainfall is meagre* a better exploitation of irrigation potential through major and minor projects, the intensive use of groundwater resources and a more efficient conservation and management of water are necessary to stabilize agricultural yields. It is important in water-balance studies to know the extent of potential demands on water through evapotranspiration. The evaporation from a free water surface and the potential evapotranspiration depend upon the radiation – incoming as well as outgoing – and the evaporative power of the atmosphere, which again is largely dependent on the saturation deficit and the air movement. In the case of potential evapo-transpiration, the extra roughness of the vegetation cover in relation to water surface is also considered. The areas of high annual potential evapotranspiration are the extreme west of Rajasthan (Jaisalmer) and the extreme south of Tamil Nadu (Tuticorin). The analysis of weekly totals of rainfall over long periods gives information on the lower limits of rainfall, week by week, that are likely to be exceeded for various percentage probability ranges from 90 percent to 10 percent. It is expected that these probability figures will be useful in the identification of periods favourable for sowing different crops and for determining the quantum of moisture that would be available during different phases of crop growth. Again, where the amount of assured moisture in a particular probability range is deficient to meet the needs of a crop in a phase, the extent to which this deficiency has to be made up by irrigation can also be determined.

During the said conditions the options available in water-limited environments are: (1) *drought escape*, where the crop completes its life before the onset of terminal drought, (2) *drought avoidance*, where the crop maximizes its water uptake and minimizes its loss and (3) *drought tolerance*, where the crop continues to grow and function at reduced water contents. Crop management offers (1) *drought alleviation* or moderation, by the means of irrigation and (2) *optimal crop water use patterns*, by reducing the evaporation during grain filling period (Ludlow, 1989). The challenge of water management at the crop level is to match the time-course (and total amount) of natural and irrigation resources with crop requirements by increasing the resources, moderating plant requirements and/or increasing soil water extraction. In arid and semi-arid regions, it is important to know the reported drought durations in growing season for irrigation scheduling, operation and management of agriculture production and also assessing water demand of a crop in drought periods, should be operated. A calendar showing crop sensitivity to rainfall guidelines are required. Agriculture drought is specifically concerned with cultivated plants, as opposed to natural vegetation, and it is characterized by estimated water demand and expected water supply (Rawls et al., 1993). They are dependent on agro-climatic and economic conditions. Water supply in arid and semi-arid area, is mainly from seasonal random precipitation. It is adequate to consider and place emphasis on a single crop grown homogenously over the major area of the region (Kumar and Panu, 1997).

Water Quality and Irrigation

Irrigation water always contains some soluble salts in it. Apart from the total concentration of the dissolved salts, the concentration of some of the individual salts, and especially of those which are most harmful to crops, is important to be determined. The suitability of water for irrigation is determined by the electrical conductivity for the total dissolved salts, soluble sodium percentage, sodium absorption ratio, the boron content, pH, cations, such as calcium, magnesium, sodium, potassium, and anions, such as carbonates, bicarbonates, sulphates, chlorides and nitrates. Water that flows over salt-affected areas or in the deltaic regions has a greater concentration of salts sometimes as high as 7500 ppm or even more. The quality of tank or lake water depends mainly on the soil salinity in the watershed areas and the aridity of the place. The quality of water from shallow or deep wells is generally poor in areas of: high aridity of arid and semi-arid regions with less than 45 cm of annual rainfall; high water-table and water-logged areas; and in the vicinity of sea-water, as in the coastal region.

A crop or a variety which is more tolerant to salt should be selected for growing under the cropping pattern adopted. Crops have been broadly grouped according to their *salt-tolerance limits* into: *Tolerant species* (over 5000 ppm salts): Barley, sugar-beet, date-palm, rape, kale, cotton, Rhodes grass and sesbania; *Semi-tolerant species* (2500 to 5000 ppm salts): Rice, sorghum, maize, barley, sunflower, lucerne, berseem or guar, safflower, onion, spinach, lettuce, carrot, cluster-bean, wheat, pearl-millet or bajra, and grasses; and *Sensitive species* (below 2500 ppm salts): Peas, cabbage, vetch, beans, gram, peaches, grapes, orange, grapefruit, potato, and tomato. The limits of relative *tolerance of crops to boron* are: *Tolerant species* (2 to 4 ppm): Date-palm, sugar-cotton, lucerne, onion, turnip, cabbage, carrot and lettuce; *Semi-tolerant species* (1 to 2 ppm): Wheat, maize, barley, cotton, sunflower, potato, tomato, peas, beans and sweet-potato; *Sensitive species* (0.3 to 1.0 ppm): Apple, apricot, grape, orange, grapefruit, plum, pear, cherry and walnut. The continual use of poor-quality water for irrigation water can be improved by adding sulfuric acid or sulfur to reduce the pH to the desired level. Gypsum is applied to the soil or mixed with water where poor quality water containing a high concentration of sodium salts is used for irrigation. The permeability of soils can be improved by incorporating organic matter into them to facilitate the leaching down of the salts beyond the root zone.

4.8 Irrigation Management Practice

Drought-related decisions are mainly strategic in context. The uncertainty on drought occurrence (predictable or not) and the type of drought (intensity, period), as discussed earlier, governs the optimal crop management schemes. Diversification of crops irrespective of land-weather suitability and availability of water is on the increase leading to crop production below the expectation of the farmers. Economic results at the farm level are greatly influenced by the amount of available rainfall when supplemental irrigation is considered. Climate probability, risk of water deficiency, existing water use efficiency and irrigation type and schedule would help in the planning of irrigation system in achieving optimum crop production.

Irrigation Management – Majority of the water drawn by the plants from the soil is lost to the atmosphere through transpiration and a small portion utilized in photosynthesis is vital for growth. Crops use large amounts of water continuously, but the rate of use depends on plant species, size, temperature, and atmospheric conditions. The factors that contribute in selection of irrigation practices are: *Crop Factors* – The water requirements of plants vary because of age, succulence of growth, and plant species. Young plants, with little top growth, require less water because they lose less by transpiration than larger plants. Plants with succulent growth usually wilt sooner, because more of the tissue is composed of water. And, plants with large thin leaves absorb and transpire water more rapidly than those with small thick leaves. *Soil factor* – Water holding capacity, the ability of a soil or media to hold water against the pull of gravity, is important because it determines irrigation frequency and influences fertility. Of the total water held in the soil, only part of it is available to the plant. Available water is the portion between the maximum capacity of the medium and permanent wilting point. Lower water holding capacity soil will require more frequent irrigation. Aeration directly influences plant growth by its effect on soil oxygen, which controls to a large extent the uptake of nutrients and water.

Water Requirements – Plants should be watered prior to wilting, and the medium (soil) should not be allowed to dry out excessively between waterings. Table 4.2 shows the duration of the crops and their water requirements.

Table 4.2: Mean crop co-efficient (Kc) at different growth stage for arid climate (FAO, 1979)

Crop	K_{c1}	K_{c2}	K_{c3}
Alfalfa Hay	0.30	1.25	1.10
Artichokes	0.95	1.00	0.95
Asparagus	0.30	0.95	0.30
Banana, 1st year	0.50	1.15	1.10
Banana, 2nd year	0.70	1.20	1.10
Barley, Wheat, Oats	0.30	1.15	0.20
Beans, Green	0.40	1.00	0.90
Beans, Dry and Pulses	0.40	1.15	0.35
Beets, Table	0.40	1.05	0.95
Berries	0.30	1.05	0.40
Carrots	0.50	1.10	0.80
Castor Beans	0.40	1.15	0.50
Celery	0.35	1.10	1.00
Citrus	0.65	0.80	0.65
Citrus w/cover or weeds	0.70	1.05	1.05
Clover Hay	0.60	1.20	1.05
Coffee	0.90	0.90	0.90
Conifer Trees	1.20	1.20	1.20
Corn, Field	0.40	1.15	0.60, 0.35
Corn, Sweet	0.40	1.15	1.05
Cotton	0.40	1.20	0.65
Cucumber, Fresh Market	0.35	0.95	0.75
Cucumber, Machine Harvest	0.35	0.95	0.95
Crucifers	0.40	1.05	0.90
Dates	0.95	0.95	0.95
Deciduous Orchard	0.50	1.00	0.65
Deciduous Orchard w/cover or weeds	0.80	1.25	0.85
Eggplant	0.40	1.05	0.85
Flax	0.30	1.10	0.20

(*Contd.*)

(*Contd.*)

Crop	K_{c1}	K_{c2}	K_{c3}
Grapes	0.30	0.80	0.40
Grass Pasture	0.80	0.80	0.80
Groundnuts	0.40	1.05	0.60
Hops	0.30	1.00	0.60
Kiwi	0.30	1.05	1.05
Lentil	0.30	1.15	0.25
Lettuce	0.30	1.00	0.95
Melons	0.40	1.00	0.75
Millet	0.30	1.10	0.25
Mint	0.60	1.10	1.10
Olives	0.40	0.70	0.70
Onion, Dry	0.50	1.05	0.80
Onion, Green	0.50	1.00	1.00
Open Water	1.15	1.15	1.15
Palm Trees	0.95	0.95	0.95
Peas, Fresh	0.40	1.10	1.05
Peas, Dry/Seed	0.40	1.10	0.30
Peppers, Fresh	0.35	1.05	0.85
Pistachios	0.20	1.10	0.40
Potato	0.40	1.10	0.75
Pumpkin	0.40	1.00	0.75
Radishes	0.30	0.85	0.80
Rice	1.10	1.25	1.00
Safflower	0.35	1.15	0.20
Sorghum, Grain	0.30	1.05	0.50
Sorghum, Sweet	0.30	1.20	0.50
Soybeans	0.35	1.10	0.45
Spinach	0.30	1.00	0.95
Squash	0.30	0.95	0.75
Strawberries	0.40	0.90	0.70
Sugar Beet	0.30	1.15	1.00
Sugar Cane	0.40	1.25	0.70
Sunflower	0.30	1.15	0.35
Tea	1.00	1.00	1.00
Tomato	0.40	1.20	0.65
Walnut Orchard	0.50	1.00	0.65
Winter Wheat	0.30	1.15	0.20

The amount of water required and the frequency of irrigation depend on the water holding capacity of the potting medium, amount of water already present in the medium, size of plant and container, species of plant, temperature, humidity and wind speed. During cloudy and/or cool weather, less frequent watering is usually adequate. *Application losses* take place during the conveyance of water through seepage and deep percolation. The irrigation efficiency depends upon the soil texture. The finer is the soil texture, the lower are the application losses and the greater is the irrigation efficiency than surface irrigation. The management practices also influence the irrigation efficiency. The levelling of the land properly, the selection of the *optimum plot size and the stream size* and the proper scheduling of irrigation depth increase the efficiency. The application losses can also be minimized by using water-control structures, such as water gates, diversion boxes and by lining the canals. *Irrigation Systems* – Key components of any irrigation system are the well, pump, and proper size main and lateral lines. Rotating sprinkler heads are best for larger container sizes and provide satisfactory coverage in calm wind conditions. Whirling, rotating sprinklers, of various designs, provide excellent coverage but the small water droplets may not penetrate when plants have a canopy over the growing medium surface. This type of sprinkler operates best in protected locations. *Drip and Trickle Irrigation system* delivers various volumes of water. They are operating at pressures varying from 40 to 60 ppi and it gets clogged because of the high calcium and magnesium levels in most irrigation waters, as well as from growth of algae and/or bacteria within the tubes.

Crop production is related to individual plant yield to water use. They are influenced by other farming inputs and crop specificities. Involuntary irrigation deficits due to low water availability, delivery uncertainties and poor management can also increase the likelihood of reduced yields. Crop production is seriously affected by unforeseen climatic variations including water (rainfall and irrigation) supply as reported mostly in tropical zones (Ellis, 1988). Deficit irrigation (English and Raja, 1996) is an optimizing strategy under which crops are deliberately allowed to sustain some degree of water deficit and yield reduction. Farmers are aware of increased crop failure potential and the enhanced risk of crop productivity due to deliberate deficit irrigation. Adoption of this method requires appropriate knowledge of crop ET, crop responses to water deficits, identification of critical crop growth periods and the economic impacts of yield reduction strategies. It also implies the adoption of appropriate irrigation schedules which are built upon validated irrigation scheduling simulation models or are based on extensive field trials. Highest Water Productivity (WP) or Water Usage Efficiency (WUE) (Oweis et al., 1998) of applied water was obtained at rates between one-third and two-thirds of full irrigation requirements (one-third and two-thirds of Supplementary Irrigation) depending on the seasonal rainfall. Planting dates interact significantly with the level of irrigation applied.

Artificial rain making – The water droplet in a cloud grows a million times its original volume, each around a nucleus present in the atmosphere to become a raindrop. In warm clouds (at temperature above freezing), the growth occurs through coalescence of water droplets and in cold clouds (where the temperatures are below freezing), the growth occurs through the formation of ice crystal. The technique of cloud-seeding aims at correcting the deficiencies of nuclei in the cloud. Silver iodide is used for seeding cold clouds whereas sodium chloride (common salt) is generally used for seeding warm clouds. The seeding is effectively done with an aircraft flying inside the cloud.

4.9 Soil Water Analysis

Most often, modelling of soil water content (water balance) is applied as a sub-model of plant growth simulation models. It has however been found that soil water or plant available water is one of the major limiting factors to plant growth. Therefore modelling soil water content can provide an indication of potential plant response to environmental/climate variation especially in dry land agriculture, which is the most abundant form of agriculture in Australia. With the ability to model potential plant response to environmental/climate variation, it is possible to use soil water balance models for the analysis of agricultural drought. The model must be carefully calibrated for the particular agriculture system and soil properties of the region, to be capable of reliably predicting plant available water and therefore provide a reliable indication of how plant growth may be affected. In its simplest form, a soil water model calculates changes in volumetric water content of the soil over a period of time, which is equal to the difference between the amount of water added (infiltration) and the amount of water withdrawn (redistribution) from the soil during a given period. Depending on the complexity of the model and availability of data, parameters of the model may vary from relatively simple (rainfall and evapotranspiration) to complex.

There are essentially three approaches to modelling infiltration and redistribution of soil water: analogue; mechanistic; and intermediate. *Analogue approaches* treat the soil as a ‘bucket’ which fills via rainfall or irrigation and empties by evapotranspiration and drainage. The properties of the ‘bucket’ are determined by the characteristics of the soil being considered, maximum soil water content is a measure of the highest storage threshold (or field capacity), a soil water content of zero represents the point at which the plant is supposedly unable to extract water (wilting point). *Mechanistic (or rationale) approaches* are more complex than the analogue approach, essentially the flux (change in available water) is controlled by the existence of soil water potential gradients. The equation used to predict ‘flow’ is derived from Darcy’s Law and the continuity principle. There are numerous ways to solve this analysis which involve discretisation of the soil profile into layers.

There are also methods which combine the analogue and mechanistic approaches, referred to as intermediate. The challenge for historical analysis of drought is to develop water balance models based upon available data which produce reliable results. Simple analytical models are often too empirical for accurate estimates of water balance and mechanistic models are often too complex for routine and regional use. Without detailed data on the characteristics of the soil in a region and therefore having the ability to reliably predict plant available water, it is difficult to justify the use of soil water models as the primary indicator for the analysis of drought impact. The availability of reliable soil data is limited to only a few disparate regions, it is therefore recommended that soil water modelling be incorporated with other indicators for analysis of drought events. Growth simulation is recognized as being applicable to the analysis of drought events because it incorporates meteorological and soil water information and therefore takes account of a variety of factors which may affect agricultural production.

4.10 Plant Growth Simulation and Drought Event Analysis

There are various well developed models available for predicting plant growth. These range from simple regression models to complex simulation models with many parameters which may have the potential to mimic soil water behaviour, effects of temperature, efficiency of water use, nutrient limitations, plant life histories, management options, inter-species competition, and so on. The range of models are capable of providing one or a combination of three important outcomes: “Analysis of observed responses of plant growth to variation of certain factors, to increase our understanding of crop growth and provide direction in our research; Simulation of plant growth by comprehensive models consisting of many interacting components and levels, as a teaching aid; and Prediction of the outcome of certain climatic or management conditions, where understanding of lower levels of organization and inclusion of details about them may take second place to accurate prediction under a defined range of conditions” (Rimmington and Charles-Edwards, 1987).

Model selection (similar to the soil water models) and the relative complexity of the chosen model relies on what information is required to run the model and the time unit chosen. Hansen and Jones (1980) state that perfect aggregate prediction at larger scales requires perfect aggregation of a perfect model across the range of variability of perfect input data. Although this is a cynical view, it is important to realise that modelling a complex system such as plant growth across a region is difficult and thwart with uncertainty. To overcome the difficulty in analysing drought throughout a region, it is appropriate to use the simulation of a single crop or pasture type grown homogeneously over the region. It is fundamental that models which aim to simulate the effects of drought on agricultural production incorporate a calculation of evapotranspiration and the depletion of soil water, involving three aspects: determination of the demand for water from solar radiation and the atmosphere; a definition of the amount of soil water available to the plants; and a calculation of the transpiration and soil evaporation rates when the water content of the soil becomes limiting (Jamieson et al., 1998). Drought triggers should be both *supply-type*, reflecting moisture deficiencies caused by acts of nature (lack of rain, excessive temperatures), as well as *demand-type*, reflecting drought impacts.

4.11 Drought Forecasting/Prediction of Events

The issue of drought forecasting has two problems such as (1) foreshadowing the initiation of drought and (2) forecasting future conditions within a drought. The first problem is difficult but apparent trends and periodicity and tele-connections may be exploited by way of modelling. The second problem may be attempted by low flow forecasting techniques. The methods for forecasting the future course of events within a drought often capitalize on the persistence in the variable of interest or in causative variables. The origin of its persistence lies in the inertia within the climatic and hydrological system, aquifer storage being the most important. Many forecasts are expressed statistically using the continuation of the recession as a lower bound and expressing the possibility of higher values in probability terms based either upon the past record or else upon rainfall statistics. Climate anomalies such as southerly shift of the inter-tropical convergence zone and blocking tendency are associated with subtropical and temperate zone droughts respectively which can themselves be sustained by conservative system. These include polar or equatorial shift of ice pack and sea surface temperature anomalies. The tele-connections have been used extensively in drought forecasting both objectively in regression equations and more temperature anomalies and inland weather.

Linear regression models involving weather variables such as air pressure, air and sea surface temperatures, wind velocities and directions and the recent record of the precipitation data are used for drought prediction. In agriculture droughts, the regression models involve crop yield, weather variables such as precipitation of the recent months, number of wet days and similar correlative variables. Time series forecasting algorithms employing ARIMA models, non-homogenous Poisson processes coupled with conditional probabilities are used for short term forecasting. There is an apparent cyclical behaviour in Indian monsoon rainfall that explains less than ten percent of the variance and therefore do not offer any forecasting possibility. Regression rate of stream flow hydrographs, stage graphs of water bodies and indices based on the status of soil moisture and vegetation in the region under consideration have been used for short-term forecasting (Zelenhasic and Salvai, 1987). A regression model for predicting monsoon rainfall anomalies from ENSO indices found 60% of the variance. Autoregressive, multiple linear regression, exponential smoothing, trigonometric regression and a qualitative approach based upon sunspot cycle, could fail due to the forecasting of the expected value of the identifiable process and random fluctuations remain the dominating and unforecastable influence.

The most commonly used time scale in drought analysis is the year followed by month. Yearly analysis is a long period and it can only portray the regional behaviour of drought. The monthly time scale is appropriate scale for monitoring drought effects related to agriculture, water supply and groundwater abstractions. (Sharma, 1996). Forecasting of drought is more important in view of the drought preparedness and early warnings. The correlation of time series of PDSI, precipitation, temperature and stream flow with ENSO events is being carried out (Corduroy and McCall, 2000). Southern oscillation index or sea surface temperature is another potential parameter for prediction of long-term drought events. Stream flow is considered as the hydrologic variable in drought analysis, in addition to unit of time for the variable for both continuous and discrete data. A hydrologic drought event is considered as an event during which stream flow is continuously below the truncation level and below-truncation-level sections, it does not need to be held constant.

Recurrence interval or return period of a hydrologic event is the average elapsed time between occurrences of an event with a certain magnitude or greater (Hann, 1997). In drought studies, the recurrence interval of hydrologic drought can be considered as the mean inter arrival time of hydrologic droughts with a certain severity or greater. It is assumed that occurrence of hydrologic drought events is observed at the beginning time 0 and the inter arrival time of events is the period of time between two successive events, namely the time elapsing from the initiation of a drought to the beginning of the next drought (Shiau and Shen, 2001). By using the theory of runs, stream flow state at a time t is either drought or non-drought. One form of the lag 1 Markov chain formula used in hydrological drought study is:

$$Q_{i,j} = Q_j + b_j (Q_{i,j-1} - Q_{j-1}) + \tau\sigma_j (1 - r_j^2)^{1/2}$$

where $Q_{i,j}$ = generated flow for month j, year i; Q_j = mean of observed flows for month j, $Q_{i,j-1}$ = generated flow for month $j - 1$, year i; Q_{j-1} = mean of observed flows for month $j - 1$; b_j = regression coefficient for relation of month j to month $j - 1$, $b_j = r_j (\sigma_j/\sigma_{j-1})$; τ = random number selected from normal distribution having zero mean and unit variance; σ_j = standard deviation of observed flows from month j; r_j = correlation coefficient describing relation of flows for month j to flows for month $j - 1$.

The first two terms are the deterministic part of the generated flow and the last term in equation $\tau\sigma_j\,(1 - r_j^2)^{1/2}$ is the random part of the generated flow with a normally distributed variance. It is to be noted that j represents the calendar month of the year. Therefore when $j = 1$ (January), $j - 1$ = December of the previous year. Hence, when $j = 1$, $Q_{i,j-1}$ becomes $Q_{i-1,j-1}$ where $j - 1 = 12$ for December and $i = 1$ represents the previous year.

The activities and regions most impacted by climatic variation must be identified in addition to the flexibility of the economy to adjust and capitalize the skillful climate forecast (Lamb, 1981). Changnon et al. (1995) found that about 3/56 of decision makers use the forecast. Forecasts are difficult to interpret, lack of models to integrate information, uncertain accuracy, additional information requirement, lack of access to expertise etc. are some of the opinion of the decision makers. Further, rural communities are not benefited by the forecasts as: (1) They are not precise enough to influence local decisions such as where to plant or where to move cattles, (2) All producers are restricted in their flexibility to respond to the forecast and (3) Forecasts are in isolation from other information and unlikely to improve the knowledge. The forthcoming predictions should address the requirements of the people who are likely to be affected by drought.

Ranking and Weightages

We could construct a drought vulnerability index by assigning weights to all the parameters that could, *ex ante*, influence drought vulnerability or the ability to withstand meteorological drought. The indicators i.e., ecological, socio-economic and production system variables were selected on the basis of their impact on the extent of drought vulnerability and then weights were assigned to them. Care was taken to ensure that the values or magnitudes of the variables moved in the same direction with respect to drought vulnerability, i.e. if the value of the variable increases the drought vulnerability decreases and vice versa. Therefore, while features like irrigation, forest cover, etc. remained unchanged, and as irrigated area or forest cover increases *ceteris paribus* drought vulnerability should decline, we took the inverse of variables like percentage area left fallow or percentage scheduled caste population, etc. Based on this all the variables were suitably treated. The bias of scale was removed by standardising the data set by using the Z score method. After standardization of the data set the individual weights of the variables were assigned and the Z scores of the variables were multiplied by these weights and row-wise summation done to get the value of each indicator for the blocks separately. All the three clusters of indicators (i.e., ecological, production system and socio-economic) were again assigned relative weights, and the final composite value for each block was computed. The indicators were summed up row-wise after multiplying the weights by the column.

Principal Component Analysis (PCA) is a branch of factor analysis which is evolved primarily to synthesize a large number of variables into a smaller number of general components which retain the maximum amount of descriptive ability. Thus it creates such a Y vector that Y's relationships with $X_1, X_2, X_3, \ldots X_m$ is maximum. Thus Y will be such that it has the maximum sum of squared correlations with the $X_1, X_2, X_3, \ldots X_m$. $r01^2 + r02^2 + \ldots r0m^2 = Z$. Thus it reduces indicators into components. PCA can only be applied when a reasonable degree of co-relation exists amongst the variables. A major problem of PCA is that a number of similar indicators result in groups of indicators pulling the other indicators in one direction.

The three production system variables that we have selected are:

1. Gross cropped area as a percentage of net sown area. This reflects intensity of cropping.
2. Gross irrigated area as percentage of gross cropped area.
3. Level of groundwater development. This reflects the extent of utilisation of the groundwater potential.

From the correlation matrix it is clear that the cropping intensity (gross cropped area as a percentage of net sown area) is lower in areas with high concentration of scheduled tribe population; high forest cover and high annual average rainfall. This is in keeping with the thesis that areas of tribal concentration are underdeveloped in terms of the concomitants or preconditions for high cropping intensity, namely irrigation and level of groundwater development. In areas of higher forest cover land use intensities ought to be higher since less land is available for cultivation.

Food security assessment involves overall crop growth monitoring on a larger area using orbital remotely sensed satellite data analysis with the help of ground-based observations. Spectral characteristics of plant growth stages and the sensors that are available in on-board satellites are highlighted in the next chapter.

References

Chagnon, S.A. (1987). Detecting drought conditions in Illinois. Illinois State Water Survey Circular, pp. 164-187.

Debaeke, P. and Aboudrare, A. (2004). Adaptation of crop management to water-limited environments. *European Journal of Agronomy*, **21**, pp. 433-446.

Ellis, F. (1988). Peasant economics farm households and agrarian development. Cambridge University Press, Cambridge.

English and Raja (1996). Perspective deficit irrigation. *Agriculture Water Management*, **32,** pp. 1-14.

Hann, C.T. (1979). Statistical methods in Hydrology. The Iowa State University Press, Iowa, USA.

Hershfiled, D.M., Brakensiek, D.L. and Comer, G.C. (1973). Some measures of agricultural drought, floods and drought. Water Resources Publications, Fort Collins, CO.

ICAR (2005). Handbook of agriculture. Indian Council of Agricultural Research, New Delhi, pp. 1302.

Kumar, V. and Panu, U. (1997). Predictive assessment of severity of agricultural droughts based on agro-climatic factors. *Journal of The American Water Resources Association*, **33(6)**, pp. 1255-1264.

Lamb, P.J. (1981). Do we know what we should be trying to forecast climatically? *Bulletin American Meteorologist Society*, **63**, pp. 1000-1001.

Ludlow, M.M. (1989). Strategies of response to water stress. *In:* Kreeb, K.H., Ritcher, H., Hickley, T.M. (eds), Structural and functional responses to environmental stresses. SPB Academic Publishing, The Hague, The Netherlands, pp. 269-281.

Oliver, H. (1961). Irrigation and climate. Edward Arnold Limited, London, pp. 250.

Oweis, T. and Zhang, H. (1998). Water-use efficiency: Index for optimising supplemental irrigation of wheat in water scare areas. *Zeitschrift f. Bewaesserungswirtschaft*, **33(2)**, pp. 321-336.

Rawls, W.J., Ahuja, L.R., Brakensiek, D.L. and Shirmouhammadi, A. (1993). Infiltration and soil water movement. *In:* Maidment, D.R. (ed), Handbook of Hydrology. McGraw Hill Book Company, New York, pp. 880.

Richer, C.B., Jacobson, P. and Hall, C. (1961). Agriculture Engineers Handbooks. McGraw Hill Book Company, New York.

Sharma, T.C. (1996). Simulation of the Kenyan longest dry and wet spells and the longest rain sums using a Markov Model. *J. Hydrology*, **178,** pp. 55-67.

Shiau, J.T. and Shen, H.W. (2001). Recurrence analysis of hydrological droughts of differing severity. *Journal of Water Resources Planning and Management*, **127(1),** pp. 30-40.

Sys, C. and Verheye, W. (1975). Principles of land classification in arid and semi-arid regions. ITC, State Univ., Ghent, Belgium.

Wilhite, D.A. and Glantz, M.H. (1985). Understanding the drought phenomenon: The role of definitions. *Water International*, **10**, pp. 111-120.

Zelenhasic, E. and Salvai, J.D. (1987). A method of stream flow drought analysis. *Water Resources Research*, **23(1)**, pp. 156-168.

Further Reading

Akinremi, O.O., McGinn, S.M. and Barr, A.G. (1996). Simulating soil moisture and other components of the hydrological cycle using a water budget approach. *Canadian Journal of Soil Science*, **75:** 133-142.

American Water Works Association (2002). Drought Management Handbook. AWWA, Denver, CO, 126 pp.

FAO (1992). CROPWAT – A computer program for irrigation planning and management. Irrigation and drainage paper no. 46, FAO Rome, Italy.

FAO (1993). CLIMWAT for CROPWAT. FAO, Rome, Italy.

FAO (1995). Water development for food security. Rome, Italy, 39 p.

FAO (2000). Deficit irrigation practices. Water paper no. 22, Food and Agriculture Organisation, Rome, Italy.

FAO (2001). AQUASTAT FAO's information system on water and agriculture. http:// www.fao.org/ag/agl/aglw/aquastat/background/index.stm

FAO (2002). Crops and drops: Making the best use of land and water. Rome, Italy, 24 p.

FAO (2003). Unlocking the water potential for agriculture. Rome, Italy, 62 p.

Gibbs, W.J. (1987). A drought watch system, WCP-134. WMO, Geneva, 23 p.

Hansen, V.E., Israelson, O.W. and Stringham, G..E. (1980). Irrigation Principles and Practice. John Wiley and Sons, New York.

Hume, et al. (1992). Seasonal rainfall forecasting for Africa. Part II: Applications and impact assessment. *International Journal of Environmental Studies*, **40**, pp. 103-121.

IPCC Working group (1998). The regional impacts of climate change – An assessment of vulnerability. Watson, R.T., Zinyowera, M.C. and Moss, R.H. (eds.), IPCC Working group, Cambridge Press, 517 pp.

Jackson, R.B., Carpenter, S.R., Dahm, C.N., McKnight, D.M., Neiman, R.J., Postel, S.L. and Running, S.W. (2001). Water in a changing world. *Ecological Applications*, **11(4),** pp. 1027- 1045.

Krishna, A. (1988). Delineation of Soil Climatic Zones of India and its Practical Application in Agriculture. *Fertiliser News*, **33(4)**, pp. 11-19.

Meinke, H., Pollock, K., Hammer, G.L., Wang, E., Stone, R.C., Potgieter, A. and Howden, M. (2001). Understanding climate variability to improve agricultural decision making. Proceedings of the 10th Australian Agronomy Conference on Science & Technology: Delivering results for Agriculture? ASA, Hobart, p. 12.

Richer, C.B., Jacobson, P. and Hall, C. (1961). Agriculture Engineers Handbooks. McGraw Hill Book Company, New York.

Rijsberman, F.R. and Molden, D. (2001). Balancing water uses: water for food and water for nature. *Thematic background paper.* Secretariat International Conference on Freshwater, Bonn, Germany, 18 p.

Soffe, R.J. (1995). The Agricultural Notebook. Blackwell Science, Oxford, pp. 532.

Wilhelmi, O.V. and Wilhite, D.A. (2002). Assessing vulnerability to agricultural drought: A Nebraska case study. *Natural Hazards*, **25,** 37-58.

5

Drought Indices

Drought indicators quantify information thereby making the significance of such information more readily apparent; simplify information about complex phenomena in order to improve communication and portray the relative and/or absolute change over the period of time in quantifying flow-on economic impacts from potential changes in agricultural production and ways of dealing with the situations such as groundwater abstraction, irrigation scheduling, and social costs. As the drought risk is not only due to meteorological but also due to socio-economic and technological changes, the ideal index should be derived from a biophysical model having strong linkages to social and economic outcomes. The main purpose of the drought index was to compare the present-day risk with that of the anticipated risk in 50 years' time assuming that there will be 30% more droughts then than now. It is important to establish benchmarks or trigger points for making critical decisions and also be important to have an indication of recovery time – the amount of rainfall required to bring the drought to an end.

Any drought index identified for the current purpose should not be used to re-litigate recent drought conditions, or be applied to such purposes as redistribution of current water rights. It is relevant to note that droughts are always disadvantageous for some, but are often advantageous for others. The index might describe both relative and/or absolute change. Indicators are needed to detect and monitor changes in the natural and social environment to provide a quantitative basis for the design of disaster risk reduction policies and to monitor the effectiveness of these policies. Indicators and thresholds represent the conceptual content of the information to be produced within an early warning system. The overall aim of establishing a threshold is to assess the change in order to determine drought risk and vulnerability. The variations in the different early warning systems are considerable and, as such, will yield differing results when compared with current data. Therefore, indicator thresholds should be region – or country-specific and modified to reflect market, climate, environment, public health and socio-economic changes. The severe drought conditions also trigger changes in species and ecosystem. Summary of the indicators that are being used in highlighting the on-set drought situation is highlighted here.

Drought index need to be *Universality* – applicable to all parts of the terrain and agro-climatological zones for both nation-wide and regional analyses. It should also be sufficiently *versatile* to cope with varying thresholds or scales of severity. *Easily interpretable* by the concerned people and should be used with the *readily available data* to enable calculation of robust anomaly and recurrence statistics. Need to enable *improved advice to farmers* for land use planning. Future *scenario generation* should be able to be formulated with the existing information and *linked to decision-making* pointers in representing the duration and intensity of drought towards potential for further research. The present-day drought indices are meteorological or agricultural or hydrological in nature. Further, they need to highlight the (1) *Accumulated deficit* based on the occurrences of water deficiency, rather than just the departure from climatological mean. (2) *Time step* – Daily units of time were essential, because a water deficit could be overcome by just a day's rainfall. (3) *Water storage term* – characterise both soil moisture and other water resource (e.g. lakes, groundwater) storage as separate features. (4) *Time dependent reduction function* in accounting for daily water resource depletion through runoff, evapotranspiration and other factors, particularly to evaluate the residual resource of rainfall that had occurred some months earlier. (5) *Modelled or estimated data* are the over *simplification of data*, hence it is better to use measured parameters only, such as precipitation. (6) *Lack of other information* – They have failed to provide good and timely information on the duration of drought, how much deficit of water had occurred, when the drought was likely to end, and how much rainfall was needed to return to normal conditions. Irrespective of available indices on different aspects, we can also synthesize the data into a single indicator on a quantitative scale as Drought index.

Drought triggers are based on threshold values of an indicator that distinguish a drought level and determine when management actions should begin and end. Triggers ideally specify the indicator value, the time period, the spatial scale, the drought level and whether progressing or receding conditions. Drought levels are categorized into mild, moderate, severe and extreme drought that forms the critical go-ahead for management plan. Hence, a drought index should be: (1) Universality – the index should be applicable to all parts of the country, and be suitable for both nation-wide and regional analyses. The index should also be sufficiently versatile to cope with varying thresholds or scales of severity. (2) Easily interpreted. (3) Supported by readily available data to enable calculation of robust anomaly and recurrence statistics. (4) Should enable improved advice to farmers for land use planning.

(5) Be an indication of production loss. (6) Suitable for subsequent research needs – e.g. land use, social implications, water policy. (7) Be based on parameters for which predictions of future change can be plausibly developed, given current knowledge. (8) Able to be linked to decision trigger points (eg. the kinds of thresholds that farmers might use to implement drought mitigation actions). (9) Represent both the duration and intensity of droughts, as both are important. Drought indicators are variables to describe the magnitude, duration, severity, and spatial extent of drought.

Drought indicators and triggers are important – to detect and monitor drought conditions; to determine the timing and level of drought responses; and to characterize and compare drought events. Operationally, they form the linchpin of a drought management plan, tying together levels of drought severity with drought responses. Several indicators can be also synthesized into a single indicator on a quantitative scale, often called a drought index. The acceptability and execution of drought indices are constrained with problems such as choice of indicators, comparability of indicators, especially between different groups (e.g. farming indicators and socio-economic indicators), continuous and discrete indicators and weighing factors of indicators.

5.1 Drought Assessment Parameters

The critical parameters that are used in drought analysis are: rainfall, temperature, evaporation, vegetation health, soil moisture, stream flow, etc. by scientists in evaluating drought situation. Continuous measurement and analysis of these parameters are used in the assessment of climatic change, spatial distribution of drought conditions etc. on a global, regional, drainage basin and local level preparedness for the event. Even though, they are measured by different agencies, it is one agency that co-ordinates the information collection, and analyses prior to declaration of any warning.

Rainfall and Temperature: Rainfall is measured at a site with the help of recording and non-recording rain gauges by various agencies spread over throughout the globe. Satellite-based rainfall estimation procedures are also used by meteorologists. Meteorological department of countries collate this information from other sources also and bring out an immediate, short- and long-term forecast. A comparison of the daily or seasonal rainfall during the cropping season would highlight the probable rainfall deficiency pattern. Normal annual rainfall and the departure on a weekly basis issued by IMD is shown in Fig. 5.1. Fluctuation in annual/monthly/daily rainfall is analyzed in the form of time-series in understanding the cyclic pattern. Normally the trough of the pattern coincides with the deficit rainfall of the region. The maximum and minimum *temperature* is measured using thermometers on a regular basis. This information is not only used to indicate the sweat factor

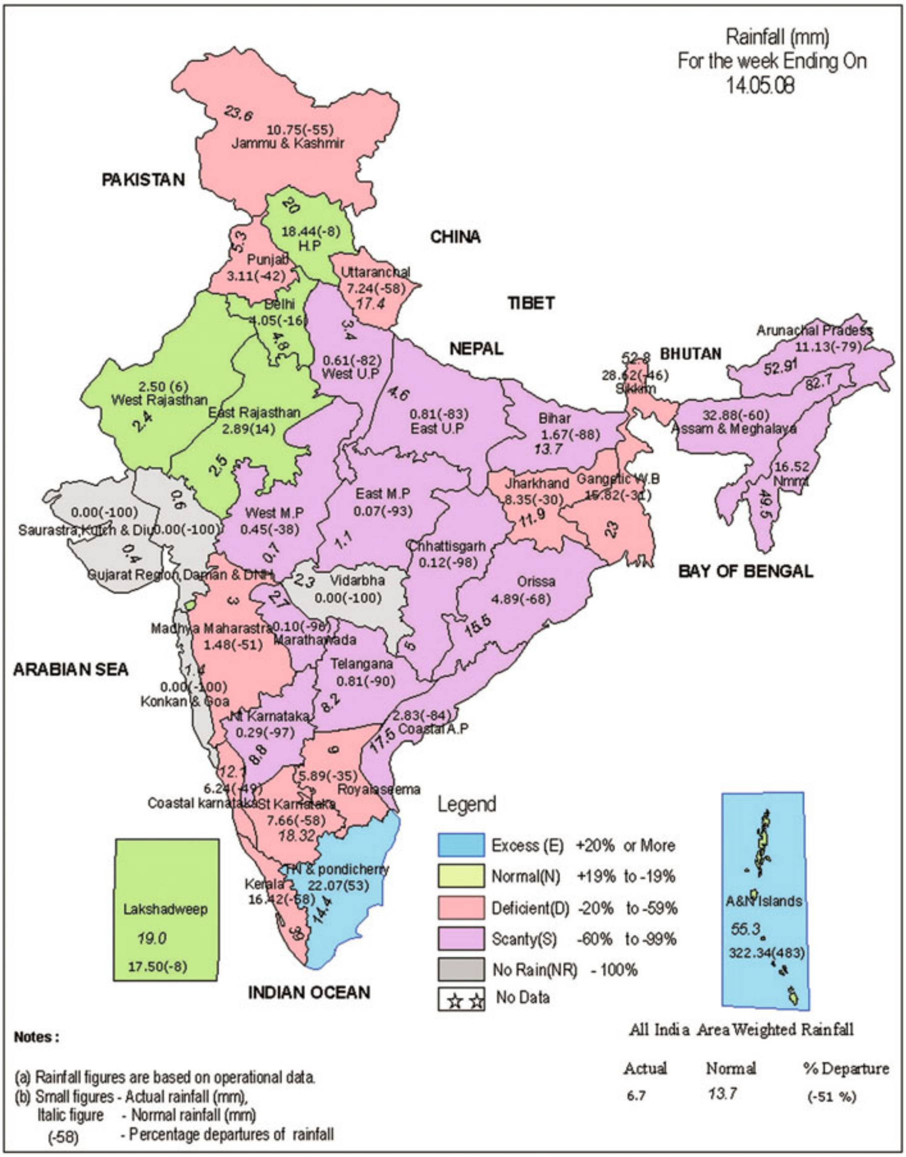


Fig. 5.1: Normal annual rainfall of India.
Source: Indian Meteorological Department, Pune

or chillness of a place, but also used in the estimation of evaporation from the surface water storage reservoirs. The empirical formulae are used in evapotranspiration and evaporation from the lakes/reservoirs. The anomaly in the pattern of temperature between the successive month, season, year or deviation from the normal indicates the prevalent changes in the region. Figure 5.2 shows the temperature anomaly of India where few pockets of

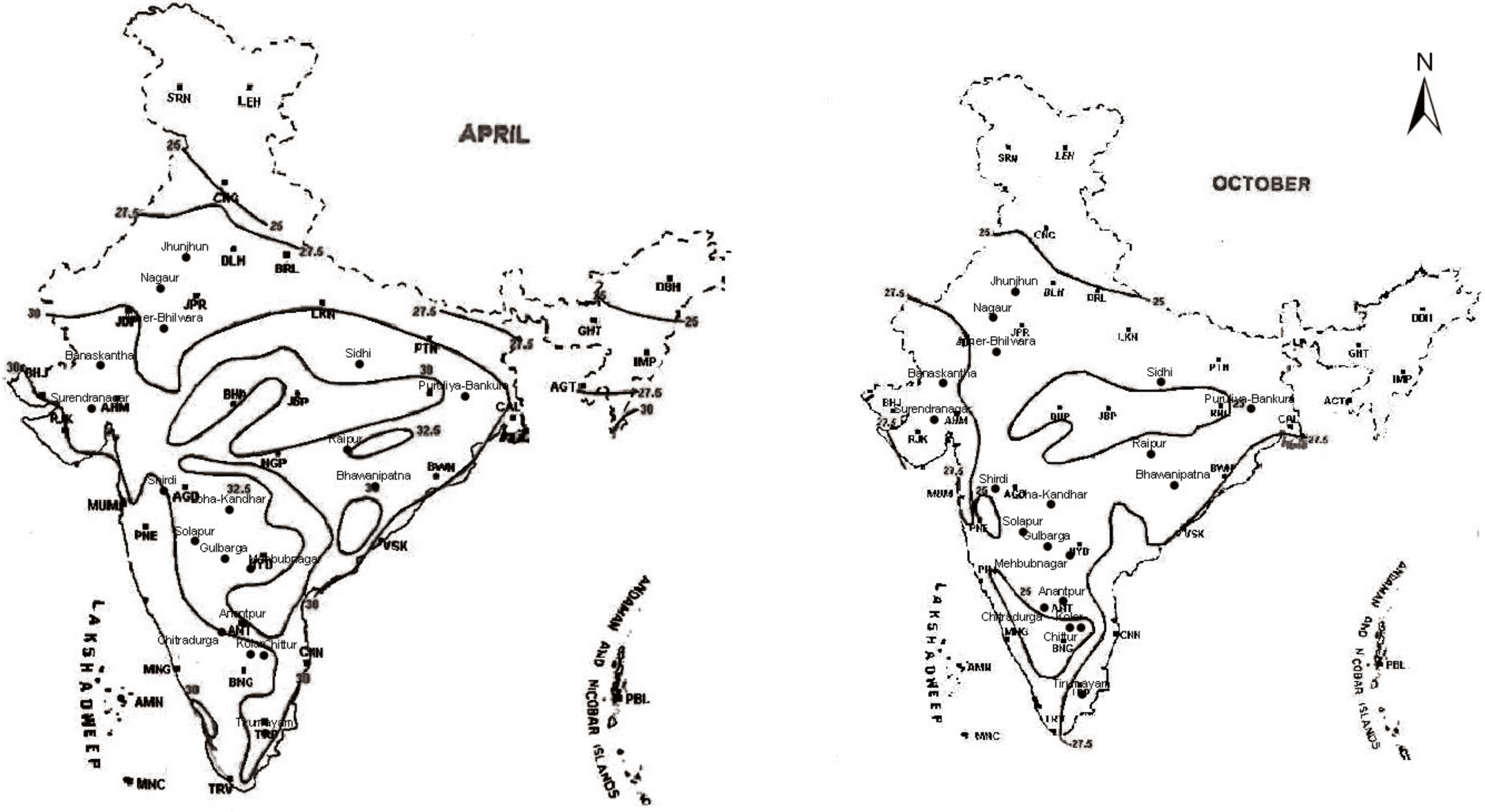


Fig. 5.2: Status of normal temperature in April and October.
Source: Indian Meteorological Department

chillness and sudden increase are observed. IMD bulletins show the areas that received annual rainfall less than 75% of the normal as drought regions and further classifies as moderate drought when it receives 25-50% of rainfall. It issues rainfall variation in the country and also probable drought regions.

Evaporation and Evapotranspiration: The amount of water that evaporates from the unit area of water surface bodies are measured by Pan evaporimeters at select agro-meteorological stations for the use of agronomists, hydrologists, irrigation engineers etc. The *evaporation* from open water surface is a function of available energy, net radiation, surface temperature, and air and wind speed. The rate of evaporation (E_O) varies from 50-75 cms (Himalayas), 325 cms (West Rajasthan) and Jalgaon-Akola region, 100-150 cms (NE India) and 150 cms (West coast of India) with time and space (Rathore and Biswas, 1989). This data can also be measured and used in the drought analysis. *Evapotranspiration* is the amount of loss from evaporation loss from the transpiration of vegetation (E_t). It varies with type of vegetation and its ability to transpire and to the availability of water in the soil. Percolation gauges and lysimeter (a large block of undisturbed soil cover with representative vegetation) are used to measure the evapotranspiration. It is found that it is 3 to 4 times greater than the colder months and also varies with relative humidity, temperature and wind speed. Penman's approach, Thornthwaite equation, Hargreaves equation, Turc's formula, Pan/evaporation method and Blaney-Criddle formulae are widely used in the calculation of potential evapotranspiration (James, 1999).

Soil moisture: The amount of soil moisture available on the top 10 cm of soil (plant root zone 200 cm) during the growth period of a crop decides its growth and yield. Further it is a key variable in controlling the exchange of water and heat energy between the land surface and the atmosphere through evaporation and plant transpiration. It is estimated from the change in the weight of soil in native and after removal of water through oven heating. However, several soil moisture sensors such as SMR-1 are available for site measurements. Passive microwave radiometric techniques operating in the 1-3 GHz measurement range are used on portable, truck and satellite mounted platforms for monitoring purpose. Regular watering through irrigation schemes replenishes the depletion of moisture that is critical during the growth and mature stage. Variation/deficiency in the soil moisture content at point or crop area with reference to the previous good yield/rainfall season indicates the probability of crop withering and loss in production. This information is collected, interpreted and disseminated to the public as a map or warnings to the farmers for revision of their watering schedules.

Reservoir water level and river flow: The availability of surface water over the lakes, reservoirs etc. from the rainfall or snowmelt and its depletion due to seepage, release for irrigation and drinking, evaporation loss etc. at a point of time and requirement during the summer/crop growth period, are critical parameters in the planning. Daily water level and volume is calculated at reservoirs. Threshold level and volume of the previous drought events were taken into consideration prior to cut in the water release or supply from the reservoir. The lack of precipitation has become a threat to water supply and it is determined by: (1) amount of water in storage, (2) anticipated water demands, (3) the severity of the precipitation deficit, and (4) specific water sources in a region. Often, government's ability to manage the situation was made difficult by not having a way to compare the severity of drought in different parts of the state/country and then communicate this information to the public. In response to these difficulties, drought indicators are devised to monitor regional water-supply sources. The indicators are designed to: (1) integrate large amounts of data about water-supply sources; (2) communicate to the public and decision-makers accurate information; (3) be reasonable; (4) based on real-time data; and (5) be distributed quickly over the public awareness campaign modes including television and Internet. Select reservoir level information during the monsoon period is provided in the newspapers to understand the status of water supply system.

River flow as the resultant of rainfall or snowmelt decides the possible amount of storage at downstream side. River flow between two stations also indicates the contribution from the spring or loss due to extraction. River gauge stations are located at major rivers and flow level at a station can be compared with the previous records in deciding the imminent drought situations in the adjoining areas. Even though, these indicators are not the triggers or causative parameters, they change the drought status significantly in supplementing the water requirements of crop and human settlements. Each of them is assigned to one of four conditions: (1) near or above normal, (2) moderately dry, (3) severely dry, or (4) extremely dry. Water-supply planners evaluate them with best professional judgement and input from surveyors and recommend an appropriate drought status for each region (normal, watch, warning or emergency).

Crop area and yield: The healthiness of vegetation indicates the availability of water and other nutrients. The plants that are not tolerant to drought (deficient water) situation either withers or dies out. The healthy vegetation assessment is carried out on ground level as well as through remote sensing methods. The shrinkage in the area of vegetation cover is considered as indirect evidence of drought situation. The percentage of production at different growth levels (flowering, matured stage) with reference to the sown indicates the damage to the crop due to non-availability of water, pests, etc. The anomaly regions could be investigated for possible additional efforts by the farmers. Agriculture authorities continuously monitor the crop area and type for possible production leading to food security planning.

Social aspects: The quality of life depends on the economic prosperity (availability of resources at an affordable stage) of the region. In the absence

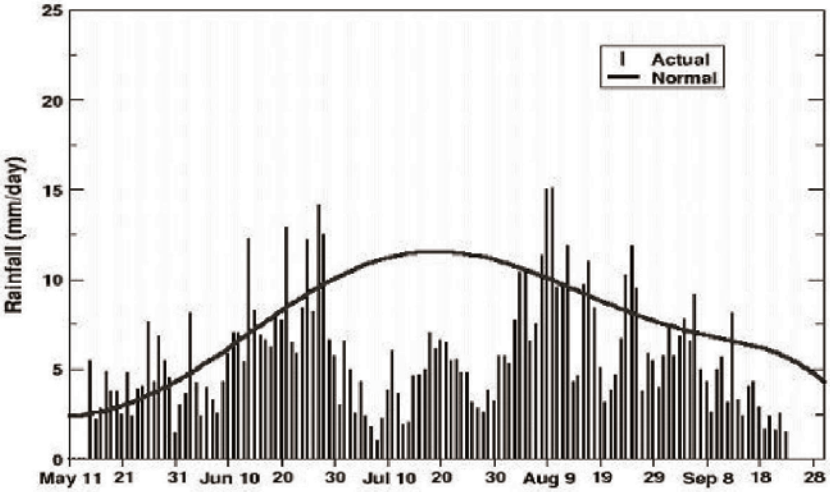


Figure. 5.3: Monsoon aberration (2002) – Varriation in actual with references to normal rainfall of a station.

of failure of monsoon, the earning potential of unorganized sector gets affected, leading to starvation, poor health of children, women and menfolk and death due to starvation of human and animals. The unemployment, starvation, non-productive nature of agriculture, industries, non-availability of drinking water source, panic selling of dwellings, etc. are considered in the declaration of socio-economic drought in India. The monitoring of revenue and hospital records of the area is collected and analyzed for this purpose. Figure 5.3 shows the monsoon aberration for the year 2002.

5.2 Indices

Different indices may be needed for different cropping systems or to adequately represent hydrological conditions. Pastoral, rain-fed agriculture will be dominant for a long time in terms of the national economy of tropical countries. It is important to distinguish between dry land and irrigated agriculture. Timing of drought is important as late season drought, after harvest, may not be important to cropping farmers. As adequate information is available now from the instrumentation placed on ground and satellite on varied scale and time period, holistic interpretations of drought can be attempted. It requires a scientific approach on the quantitative index of shortage.

Indicators and techniques described below are proven to provide some measure of the effect of environmental and climatological variation on agricultural production. Even though they are developed and tested at different climatic zones, people have modified and used them with partial or full success. Due to the fact that no one technique or indicator can be considered as ‘perfect’, a selection of these are most often incorporated in models dealing with drought.

5.3 Meteorological Indicators

It is defined on the basis of the degree of dryness (in comparison to normal or average amount) and the duration of the dry period. It also should consider the region specific atmospheric conditions that result in deficiencies. Some people use it as the departure of actual precipitation to average amount of monthly, seasonal or annual rainfall.

Normalized Deviation (ND)

$$ND = (P_{tot} - P)/P \qquad (1)$$

where P_{tot} is the total annual precipitation in mm for a particular year and P is the average annual rainfall for the area. The precipitation normally does not exceed double the mean precipitation in drought-prone area. Hence the deviation ranges between +1 and –1. The negative index always indicates the deficiency in rainfall. Figure 5.4 shows the annual rainfall and mean recorded at Nanded. Three year moving average of the annual rainfall of Nanded (Fig. 5.5), Parbhani (Fig. 5.6) and Loha (Fig. 5.7) indicating a present-day normal trend, ascending trend and declining trend of successive years of rainfall. The quantity of rainfall can be extrapolated from the figure.

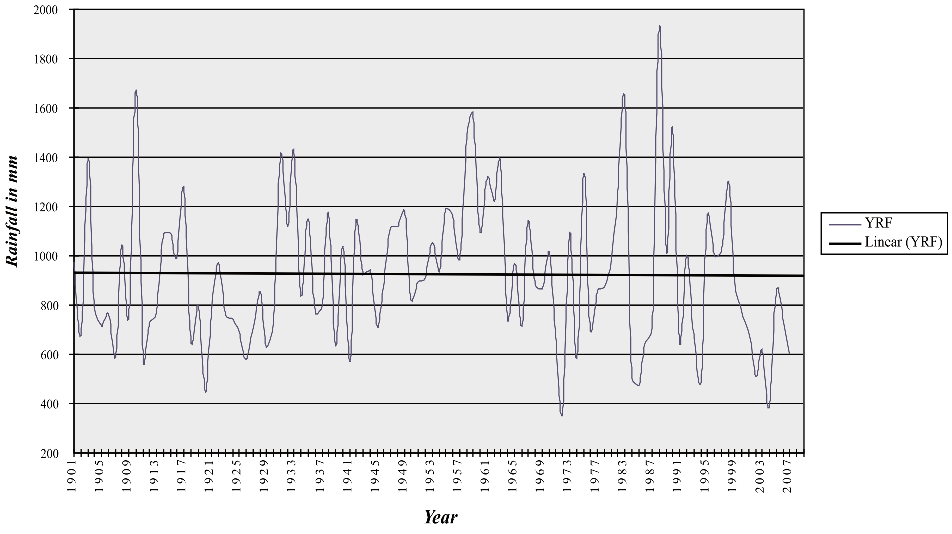


Fig. 5.4: Annual rainfall analysis – Nanded station.

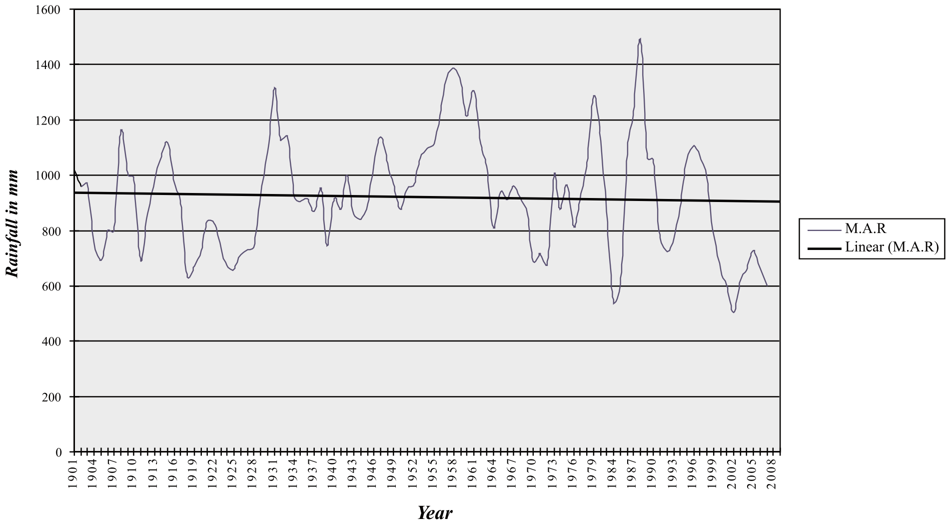


Fig. 5.5: Three-year moving average yearly rainfall – Nanded station (no significant change).

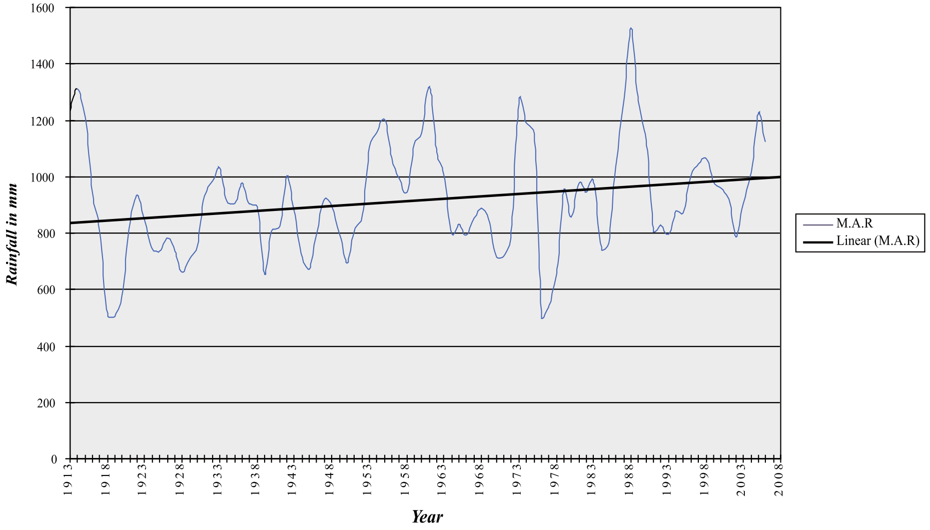


Fig. 5.6: Three-year moving average yearly rainfall (ascending mode) – Parbhani station.

Dryness Index (Id)

$$I_d = 56 \times \log_{10} (120 \times T)/P \qquad (2)$$

where T = annual average temperature in ^{o}C and P = annual average precipitation in mm. The index becomes positive for dry climatic region and negative for moist climates. It is classified as arid extreme if >72; arid moderate 50-71 and arid mid <50.

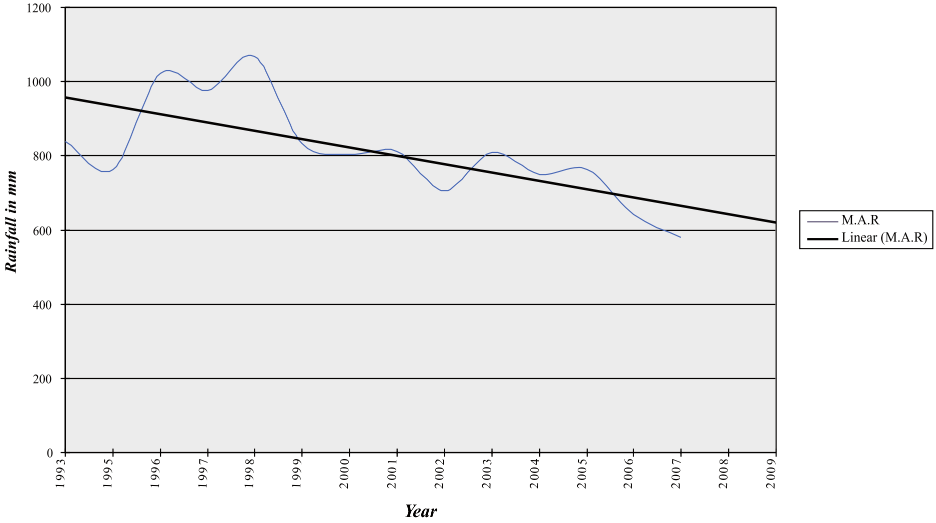


Fig. 5.7: Three-year moving average yearly rainfall (descend mode) – Loha station.

De Martonne's Index (I_A)

$$I_A = P/(T - 10) \tag{3}$$

If the index is >5, it is considered as true desert; 5-10 as arid zone and 20-30 semi-arid zone.

Pluvothermic Quotient (PQ)

$$PQ = (100 \times P/(T_M + T_m) (T_M - T_m) \tag{4}$$

where P is the precipitation in mm, T_M is average maximum temperature in the hottest month and T_m is the average minimum temperature in coldest month. If PQ is < 40 it is desert, 60-100 semi-arid zone and >300 is humid zone.

Aridity implies a high probability of rainfall for a given period below a low threshold. Drought implies a low probability of rainfall for a given period below a relatively low threshold. Thus establishing drought criteria is less meaningful for arid zones since the prospects of receiving useful rainfall are significantly lower there than in more abundant rainfall zones. Rainfall in arid zones, as well as being low, is usually highly variable in space and time, and natural pastures and herbage are strongly resistant to such stresses. Drought in an arid zone is generally more appropriate to longer periods, e.g. a year or more, rather than to periods as short as three consecutive months.

Aridity Anamoly Index (AI) of Thornthwaite (1957), describes the expression of water deficiency by the plants.

$$\text{Aridity Index (AI)} = (\text{PE} - \text{AE/PE}) \times 100 \quad (5)$$

where PE is the water need of the plants (also known as potential evapotranspiration), AE is actual evapotranspiration and PE – AE denotes the deficit. Penman's modified equation and AE compute PE from water balance procedures, which consider the water holding capacity of soil. AI signifies the water shortage from a long-term climatic value. The difference between the actual AI for the week (Fig. 5.8) and the normal aridity intensity is estimated and are grouped into mild arid (0-25), moderate (26-50) and severe (>50) by Indian Meteorological Department.

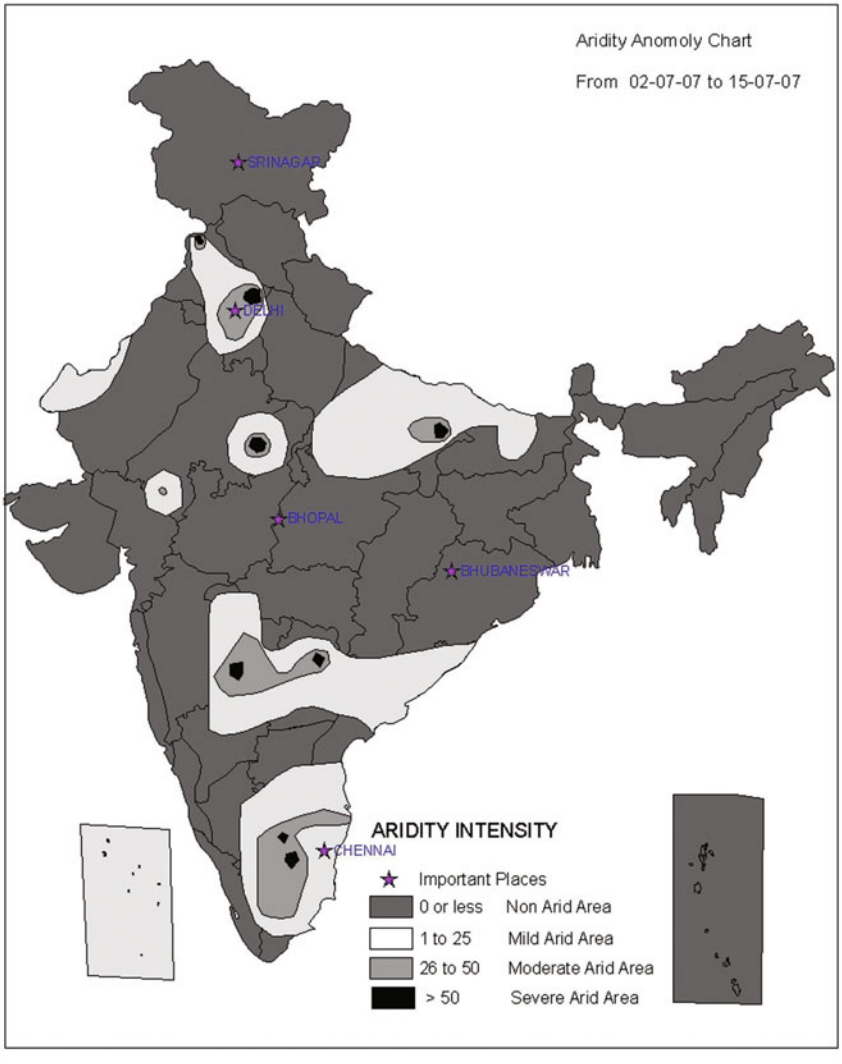


Fig. 5.8: Aridity anamoly.
Source: Indian Meteorological Department, Pune

Climatology of dry spells was computed using eight variables (calculated) such as (1) length of dry spell expressed as number of consecutive dry days (LH), (2) rainfall cumulated during dry spell, (3) cumulative potential evapotranspiration during dry spell, and (4) water deficit computed as the difference between cumulated rainfalls and ET_0. We computed additional variables measured in the 180 days preceding the start date of each dry spell, including: (5) proportion of dry days (LH6), (6) cumulated daily rainfall (PR6), (7) cumulated daily ET_0 (ET_06), and (8) cumulated daily water deficit computed as the difference between cumulated rainfalls and ET_0 measured along the 180 days preceding the dry period (DF6). A period of 6 months preceding the beginning of each dry spell was considered adequate to depict the climatic conditions of the season.

Drought severity index (DSI) developed by Salvati et al. (2005) is based on: (1) identification of dry days and characterization of dry spells; (2) computation of dry spell climatology; and (3) assessment of drought severity through dry spell climatology. *Dry spells* were considered as enough long periods during which rainfall is consistently below a fixed threshold. If the daily precipitation was <10 mm then it is grouped as dry spell. This threshold was obtained by dividing the average annual precipitation (340 mm) (Brunetti et al., 2002) and the mean number of rainy days (90 days) in Italy. The use of an absolute threshold allows an easier comparison of the results from different climatic regions. The distribution of dry spell length was truncated to 10 days in order to avoid considering too short periods to identify dry spells.

Assessment of drought severity – Each day of the year was classified as dry or wet and, if dry, the length of the current dry spell (expressed as the number of consecutive dry days before the *i*-th day), was associated to the *i*-th day as well as the mean daily rainfall, ET_0, and water deficit. To the same variables, the corresponding percentile figure obtained from climatological statistics of dry spells was associated on a day basis. If *i*-th day is classified as wet, the associated percentile for each variable considered is undetermined, as the climatology considered only the dry periods. To obtain a complete classification of the whole days (i.e., including wet days) we considered the climatic situation occurred during the earlier 180 days by calculating the variables LH6, PR6, ET_06, and DF6. The corresponding percentile was daily associated to the value of the variables LH, PR, and DF. We therefore obtained, for each dry day, the percentile of the eight variables considered in terms of both current dry spell (LH, PR, ET_0, DF) and climatic conditions in the past six months (LH6, PR6, ET_06, DF6) and, for each wet day, the percentile of the four variables LH6, PR6, ET_06, and DF6.

Finally, to obtain a synthesis of the whole information gathered, two indexes of drought conditions, namely drought duration and intensity indexes, were calculated. Drought duration index (LHS) refers to the length of dry spells, and was evaluated for each wet day as the percentile associated to the variable LH6 and for each dry day as the maximum between LH and LH6 percentiles. Drought intensity index (DFS) refers to the water deficit during dry spells, and was calculated for each wet day as the percentile associated to the variable DF6 and for each dry day as DF6 percentile under the condition that LH percentile is less than LH6 percentile. Under the condition that LH percentile is greater than LH6 percentile, the percentile associated to water deficit variable was DF percentile. Finally, the drought duration and intensity indexes were aggregated into DSI index by calculating the geometric mean of the two indexes.

Precipitation deficits often are referenced directly in native units such as inches at a particular location, but if one wants to examine drought over a large area, these values must be given in terms that are comparable from place to place. The spread of annual climatological normals from 50 inches to 15 inches means that although a 10-inch annual deficit might be 20% of the expected total for the region, it would be more than 66% of the expected total in the environments of the western Plains. Therefore, ratios or percentages are often used in establishing thresholds of precipitation deficits corresponding to droughts.

One set of planning tools that water resource managers and others find useful are maps and tables of the percent of normal precipitation expected during droughts at selected return periods and durations. The advantage of a return period, or frequency, analysis is that it assigns a degree of likelihood to the precipitation deficit. This allows users to choose the level of protection from drought in their planning and operations. There is one misconception about using return periods. A 100-year return period value is the amount of precipitation expected once every 100 years on an average. The actual time interval between two droughts of such magnitude will vary because what is really expressed in a 100-year return period is the amount of precipitation with a one percent chance of occurring in any given year. Therefore, after a 100-year return period event, one does not have to wait a full 100 years for the next event. It has a small chance of occurring in any year.

Percent of normal of precipitation is one of the simplest methods and best suited for the needs of general audiences through TV, in expressing the variation. It is estimated by dividing the actual precipitation by normal precipitation (30 years mean) and expresses it as percentage. Percentile classes (drought occurs when rainfall over a period is within the lowest decile) form part of the national drought watch scheme in Australia. If the variability of rainfall is greater than that of evapotranspiration, the anomalies of rainfall can be considered as the main cause of drought due to the changes in its amount and distribution.

Precipitation deciles: It is commonly used in Australia (Coughan, 1987). It is non-parametric method to describe the distribution of rainfall totals (Gibbs and Mather, 1967). Annual rainfall totals for a long series of years are arranged in an ascending order (from lowest to highest) and are split into 10 equal groups (like ranking). *Serious rainfall deficiency* – rainfall lies above the lowest 5% of recorded rainfall but below 10% (decile value 1) for the period in question. *Severe rainfall deficiency* – rainfall is among the lowest 5% for the period.

Decile classification	
Deciles 1-2, lowest 20%	Much below normal
Deciles 3-4, next higher 20%	Below normal
Deciles 5-6, middle 20%	Near normal
Deciles 7-8, next higher 20%	Above normal
Deciles 9-10, highest 20%	Much above normal

The first decile is simply that amount of rainfall which is exceeded on ninety per cent of occasions for the period of the year specified, e.g. winter, spring or indeed any period of consecutive months. Thus an area is categorised as having a rainfall deficiency when the rainfall for a period of at least three months falls within the lowest ten per cent (below the first decile) of the historically recorded rainfalls for the same period of the year.

The concept of rainfall deficiency is based on a comparison of the rainfall total for at least three months in a specific area with the historical long period record for those three or more months. The terms serious and severe rainfall deficiency are defined as: (1) a serious rainfall deficiency exists for a specific period of three (or more) months when the rainfall is above the lowest five per cent of recorded rainfalls, but is less than the ten per cent value; and (2) a severe rainfall deficiency exists for a specific period of three (or more) months when the rainfall is among the lowest five per cent of recorded rainfalls. When serious or severe deficiencies exist in an area they continue as such until: (a) rainfall for the past month is already sufficient to rank in the 30th percentile or greater of the recorded rainfalls for the three-month period starting with that month (a break due to relatively heavy rainfall), or (b) rainfall for the past three-months ranks in the 70th percentile or greater of the recorded rainfalls for the corresponding three-month period (a break due to a series of lesser but overall significant falls). Rainfall deficiency criteria based on decile values provide the basis for alerting to incipient drought and monitoring the course of extant drought.

Description of Possible Impacts Indicator Percentiles adopted by Arizona, USA: *Normal Conditions* (>40.00); *Abnormally Dry* – Measurable reduction in precipitation, stress to seasonal grasses, stock pond storage somewhat reduced (25.01-40.00); *Moderate Drought* – Noticeable reduction in precipitation, some vegetation stress, stock pond storage reduced, reduced stream flows, lower than average reservoir levels (15.01-25.00); *Severe Drought* – Long-term reduction in precipitation, low snow pack, reduction in reservoir levels, vegetation stress affecting trees and shrubs, habitat and pasture degradation (5.01-15.00); *Extreme Drought* – Multi-year precipitation deficits (including snow pack), significant reduction in reservoir levels, measurable reduction in groundwater levels, near-record low stream flows, substantial stress on trees and significant rangeland degradation, diminished wildlife populations (<5.00).

Precipitation Index is estimated by comparing current precipitation amounts (based on the water year) with historical precipitation values as a percent of *normal precipitation*. Normal is defined as the mean precipitation for a thirty-year record for the area and time period being evaluated. It is evaluated by comparing *current conditions* to natural conditions within the period of record. In this way, it can be determined if a current deficit is within a commonly experienced range, or whether it is unusually large. A higher percentage of this rainfall or snowfall ends up recharging the groundwater system, which sustains the stream flows and groundwater levels during dry periods. Deficits during this time are more critical for later water levels than deficits during the growing season. If a precipitation deficit outside of the normal range exists at the end of a water year, the precipitation records will carry forward until a normal condition is reached. The indicators will be used in conjunction with the condition of water supplies. Precipitation deficit changes with the progress of water year.

Drought condition

Normal	1 month below normal
Advisory	2 months cumulative below 65% of normal
Watch	3 months cumulative <65%
	6 months cumulative <70%
	12 months cumulative <70%
Warning	3 months cumulative <65% and 12 months cumulative <65%
	6 months cumulative <65% and 12 months cumulative <65%
	3 months cumulative <65% and 6 months cumulative <65%
Emergency	As that of warning and Previous month warning or Emergency

Standardized Precipitation Index (SPI) is based on the cumulative probability of a given rainfall event occurring at a station (McKee et al., 1993). The historic rainfall data of the station is fitted to a gamma distribution that is found to fit the precipitation distribution quite well. This is done through a process of maximum likelihood estimation of the gamma distribution parameters, α and β. In simple terms, the process described above allows the rainfall distribution at the station to be effectively represented by a mathematical cumulative probability function. Therefore, based on the historic rainfall data, an analyst can then tell what is the probability of the rainfall being less than or equal to a certain amount. Thus, the probability of rainfall being less than or equal to the average rainfall for that area will be about 0.5, while the probability of rainfall being less than or equal to an amount much smaller than the average will also be lower (0.2, 0.1, 0.01 etc., depending on the amount). Therefore if a particular rainfall event gives a low probability on the cumulative probability function, then this is indicative of a likely drought event depending on the time scale.

Alternatively, a high rainfall event with a high probability on the cumulative probability function is an anomalously wet event. Therefore, the SPI can effectively represent the amount of rainfall over a given time scale, with the advantage that it provides not only information on the amount of rainfall, but that it also gives an indication of what this amount is in relation to the normal. Such information helps to define whether a station is experiencing drought or not. Its output is in units of standard deviation from the median based on the record length. The longer the period used to calculate the distribution parameters, the more likely you are to get better results (e.g., 50 years better than 20 years). SPI could be calculated for all the months/weeks within the drought event and the SPI values are correlated to suitable drought conditions. As it uses regional data, there should be greater concern about the selection of variable and its duration/areal integration. Drought maps in USA show the Palmer Index, as a smoothly contoured quantity for the day and predictions for the forthcoming one, three, six and ten months.

Indian Meteorological Department expresses rainfall anomalies as constant values within designated meteorological subdivisions (Parthasarathy et al., 1987). It is very good at detecting encroaching drought conditions and can examine drought conditions over multi-year periods. It also provides an easy way to identify the beginning and end of drought conditions and to describe drought severity. State governments use this index for drought declaration. Period of rainfall deficiency is considered to be terminated if one month exceeds 200% of the mean or two months together exceed 250% of the mean or three month together exceed 300% of the mean.

Bhalme & Mooley Index is also known as Accumulated Negative Moisture Index (NMI). The NMI values are classified between normal and extreme Palmer's drought intensity classification.

$$\text{NMI (M)} = 100\,(P_{\text{mtot}} - P_{\text{mmean}})/e \qquad (6)$$

where P_{mmean} is the monthly mean over N years of observation; P_{mtot} – total monthly rainfall; M – month under consideration and e is the standard deviation. NMI demarcates the boundary conditions between monthly moisture conditions.

NMI	*Weather Characteristics*
4.00 or more	Extremely wet
3.00 to 3.99	Very wet
2.00 to 2.99	Moderate wet
1.00 to 1.99	Slight wet
0.99 to –0.99	Near normal
–1.00 to –1.99	Mild drought
–2.00 to –2.99	Moderate drought
–3.00 to –3.99	Severe drought
– 4.00 or less	Extreme drought

Potential Evapotranspiration Deficit (PED) measures and incorporates climatic factors such as how much rain falls, how high temperatures are, and how much wind the country experiences. Accumulated PED is the amount of water that would need to be added to a crop over a year to prevent loss of production due to water shortage. The accumulated PED is calculated over a July to June ‘growing year’, from daily information stored in NIWA’s climate database. PED is measured in millimetres (like rainfall), and can be thought of as the amount (depth) of water we would need to supply for a crop, in addition to observed rainfall, to prevent loss of optimum production through water shortage. PED is derived from a water balance model for the topsoil, which accounts for water gain from rainfall and loss from evapotranspiration. Evapotranspiration is the loss (or consumption) of water from an extended area of a short green crop (e.g., pasture) to the atmosphere through evapotranspiration (from the soil and other surfaces) and transpiration (from plant leaves and stems). Potential evapotranspiration (PET) refers to the maximum amount of water a crop can consume to meet both its physiological requirements and atmospheric demand when it is well supplied with water. When the crop is short of water at times of low rainfall, a gap develops between the potential water consumption (PET) and what the plant is actually consuming because of the dry weather. This gap is referred to as the potential evapotranspiration deficit, or PED. This is approximately equivalent to the amount of water that would need to be added by rainfall or irrigation to keep pasture growing at its daily potential rate. Thus, as discussed, the accumulated PED is the amount of water that would need to be added to a crop over a year to prevent loss of production due to water shortage.

Palmer Drought Severity Index (PDSI) is a soil moisture algorithm calibrated by Palmer (1964) for relatively homogenous area and not for mountainous areas, based on the precipitation, temperature and local Available Water Content (AWC) of soil. It uses a water balance model with two layers of soil and the content of the surface layer (Ss) is assumed to have a maximum of 25 mm. Human impacts such as irrigation are not considered. The content of the underlying layer (Su) has a maximum dependency on the soil type.

In this model, water transfer into or out of the lower layer only occurs when the surface layer is full or empty. The water balance equation is made up of eight variables combined in four sets. The first set is made up of potential and actual evapotranspiration. The second set is made up of potential and actual recharge. The third set is made up of potential and actual runoff and the last set is made up of potential and actual loss. The potential evapotranspiration for each month is calculated from the monthly temperature using a variation of Thornthwaite's method. The seven other variables are then calculated using potential evapotranspiration and monthly precipitation. These are used to calculate four coefficients representing the normal ratio for these sets. With these coefficients calculated, a departure from the normal moisture levels, d, can be computed. The Z-index is the name given to the moisture anomaly, which represents how wet or dry it is during a given period without regard for historical trends. It is basically the moisture departure, d, adjusted by a weighing factor called the climatic characteristic and denoted by K. All the basic terms of water balance equation can be determined including evapotranspiration, soil recharge, run off and moisture loss from the surface layer. It is no longer a meteorological index, but becomes a hydrological index and often referred as Palmer Hydrological Drought Index, because it is based on moisture inflow, outflow and storage. The PDSI is based on the supply-and-demand concept of water balance equation and takes into account the role of the soil moisture. The original monthly PDSI relies on an empirical formula derived by Palmer in 1965 using data from nine stations. The self-calibrating PSDI actually adjusts the value of K necessary to obtain the correct range of PDSI values (–4.0 to +4.0). In computing the final PDSI (X), three intermediate variables are used. The variable X_1 is the index for all wet spells before they become established and is always greater than zero. X_2 is the index for all dry spells before they become established and is always less than 0. X_3 is the index for any established spell, wet or dry. The final PDSI value is then chosen from one of these depending on the current trend. It varies roughly between –6.0 and +6.0 and the classification scale of moisture condition.

It responds slowly, changes little from week to week, and reflects long-term moisture, runoff, recharge and deep percolation, as well as evaporation. Although the Palmer Index will not be useful for monitoring monthly or more frequent changes in drought status, and thus is not a suitable indicator for purposes of this drought management plan, the Index will be monitored as applicable for reflecting the long-term status of water supplies in aquifers, reservoirs, and streams. It is hydrological accounting system that relates drought severity to the accumulated weighted differences between actual precipitation and the precipitation requirement of evapotranspiration and popularly used in the United States. It is calculated based on the precipitation, temperature and available soil water content and, thus, water balance equation can be determined. It is effective in determining the long term drought (several months) and not short-term (weeks). It is effective for measuring impacts sensitive to soil moisture conditions – agriculture. It provides a measurement of abnormality of recent weather of a region to decision-makers, an opportunity to place current conditions in historical perspective and spatial and temporal representation of historical droughts. The beginning and end of a drought or wet spell were arbitrarily selected based on Iowa and Kansa state conditions. It may not be accurate while representing the two soil layers, sensitive to AWC of a soil, snowfall, snow cover and frozen ground conditions that are considered in this calculation and natural lag between the fall of the precipitation and resulting runoff is not incorporated.

Long-Term Palmer Drought Severity Index depicts prolonged (months, years) of abnormal dryness or wetness. It also responds slowly, changes little from week to week, and, as in earlier case, reflects long-term moisture, runoff, recharge and deep percolation, as well as evaporation. Though not a suitable indicator for this drought management plan, the Index will be monitored as applicable for reflecting the long-term status of different water supplies. The main deficiency of analyses based on rainfall alone is that plant production is related to the 'use' of water and only indirectly to its 'supply'. Water use may be greater than rainfall in situations where there is depletion of soil water or less than rainfall when there is runoff or infiltration below the root zone. Other deficiencies of simple rainfall analyses are that interception losses are ignored, and all rainfall, irrespective of the season in which it falls or the amount in a particular storm, is erroneously considered to be of equal value. Furthermore these analyses ignore the soil as a storage buffer.

SPI Values		*Palmer Classification*	
2.0 and more	Extremely wet	4.0 and more	Extremely wet
1.5 to 1.99	Very wet	3.0 to 3.99	Very wet
1.0 to 1.49	Moderately wet	2.0 to 2.99	Moderately wet
–0.99 to +0.99	Near normal	1.0 to 1.99	Slightly wet
–1.0 to –1.49	Moderately dry	0.5 to 0.99	Incipient wet spell
–1.5 to –1.99	Severely dry	0.49 to –0.49	Near normal
–2 and less	Extremely dry	–0.5 to – 0.99	Incipient dry spell
		–1.0 to –1.99	Mild drought
		–2.0 to – 2.99	Moderate drought
		–3.0 to –3.99	Severe drought
		– 4.0 and less	Extreme drought

Reclamation Drought Index (RDI) is calculated at a river basin level, and incorporates the supply components of precipitation, snow pack, stream flow, and reservoir levels. It is a tool for defining drought severity and duration and also for predicting the onset and end of periods of drought. It is adaptable to each particular region and its main strength is its ability to account for both climate and water supply factors. It is unique for a river basin.

RDI Classifications			
4.0 or more	extremely wet	0 to –1.5	normal to mild drought
1.5 to 4.0	moderately wet	–1.5 to –4.0	moderate drought
1 to 1.5	normal to mild wetness	–4.0 or less	extreme drought

Some of the indicators described above are region or agro-climate specific in nature. Prior to their use the positive and negative aspects described below may be carefully examined.

Indices	*Constraints*
Deciles provides accurate statistical measurement of precipitation	Require a long climatic data record for accuracy
PDSI is a soil moisture algorithm calibrated for relatively homogenous region	Its values may lag emerging drought by several months; not suited for mountainous or frequent climatic extreme areas; complex in nature
SPI computed for different time scale, provide early warning and help in assessing drought severity	Values would change according to preliminary data
Crop Moisture Index (CMI) reflects moisture supply in short term across major crop producing region and not for long term drought assessment	Identifies potential agriculture droughts
SWSI compliments PDSI; calculated for river basin scale based on snow pack and river flow Represents water supply conditions of basins	Change in data collection station or water management practices require new algorithm. Unique to each basin
RDI is estimated on river basin scale incorporating temperature, precipitation, snow pack, stream flow and reservoir levels	Inter basin comparisons are limited

5.4 Hydrological Indicators

Hydrological droughts are the periods of time when natural or managed water systems do not provide enough water to meet the human and environmental requirements, owing to natural shortfalls like precipitation or stream flow. The persistence of hydrological drought for 20 or more years is attributed to several land surface processes.

The lack of precipitation has become a threat to water supply and, as already discussed, it is determined by: (1) amount of water in storage, (2) anticipated water demands, (3) the severity of the precipitation deficit, and

(4) specific water sources in a region. Often, government's ability to manage the situation was made difficult by not having a way to compare the severity of drought in different parts of the state/country and then communicate this information to the public. Precipitation, stream flow, reservoir levels, and groundwater levels are the dependable realistic drought indicators for situation/ event planning. Though these indicators are not the triggers or causative parameters, they change the drought status significantly. Each of them is assigned to one of four conditions: (1) near or above normal, (2) moderately dry, (3) severely dry, or (4) extremely dry. They could be updated weekly during dry periods and the results can be made available. Ultimate Irrigation Potential is the maximum capacity to irrigate by utilizing all the available water resources potential. Water-supply planners evaluate them with best professional judgement based on input from surveyors and recommend an appropriate drought status for each region (normal, watch, warning or emergency). Hydrological drought usually is slow to develop and persists longer than meteorological drought.

Surface Water Supply Index (SWSI) is calculated for river basins, based on snow pack, stream flow, precipitation, and reservoir storage. It represents water supply conditions unique to each basin thereby limiting inter-basin comparisons.

Hydrological and climatological features are blended into a single index for a major river basin, so that it could be compared with other basins. Snow pack, stream flow, precipitation, and reservoir storage are the inputs for SWSI. The procedure is as follows: monthly data are collected and summed up for all the precipitation stations, reservoirs, and snow pack/stream flow measuring stations over the basin. Each summed component is normalized using a frequency analysis gathered from a long-term data set. The probability of non-excellence – the probability that subsequent sums of that component will not be greater than the current sum – is determined for each component based on the frequency analysis. This allows comparisons of the probabilities to be made between the components. Each component has a weight assigned to it depending on its typical contribution to the surface water within that basin, and these weighted components are summed to determine a SWSI value representing the entire basin centered on zero and has a range between –4.2 and +4.2. The SWSI has been used, along with the Palmer Index, to trigger the activation and deactivation of the Colorado Drought Plan.

Stream flows can be integrated with other indicators, such as soil moisture, groundwater, and precipitation. It can also be heavily influenced by anthropogenic factors, such as developments and diversions. Stream flow gauges represent the measure of stream flow that arrives into a reservoir which caters to the settlements. Using seven-day average flows, the median flow for the evaluation period will be compared with low flows representing historical occurrence frequencies of 25%, 10% and 5% for the same date for the period of record. A 25% frequency equates to a one in four-year occurrence, 10% frequency a one in 10-year occurrence and 5% frequency a one in 20-year occurrence. The gauges should be selected on the basis of the availability of “real-time” data, as well as a sufficient period of historical record. This is the departure from average for actual aggregated stream flow heights. The historical record varies in age by station; see *underlying data* for the actual age of each station. Activities that would alter/affect the surface flow need to be considered in comparing the time series information. This index is of no relevance where settlements/villages depend on lakes and groundwater.

Drought condition

Normal	month below normal
Advisory	2 out of 3 consecutive months below normal
Watch	4 out of 5 consecutive months below normal
Warning	6 out of 7 consecutive months below normal
Emergency	> 7 consecutive months below normal

Reservoir Storage Index – Reservoir levels and reservoir storage are easy to measure yet operating rule curves may complicate assessments of drought conditions. Reservoirs are designed to provide adequate storage when demand exceeds reservoir inflow. As the stream flows are lowest during the summer period and demand is also greatest, the most critical time begins at the onset of summer. Adequate storage is presumed enough to last for a four-month period or 120 days. Water supply problems in smaller reservoirs will be taken into account when evaluating problems related to specific water suppliers. These reservoirs are too small to indicate overall water supply conditions. Some of the regions may not have any reservoir systems, so that indicator cannot be factored into triggering drought stages. Tanks, ponds, lakes and other surface improved storage systems providing water supply are widespread in India, Sri Lanka and other countries. Age of the storage system and their sedimentation levels need to be incorporated at regular interval. This index is of relevance where the water supply is dependent on reservoir.

Drought condition

Normal	Level at normal for this time of the year
Advisory	Small index reservoirs below normal
Watch	Medium index reservoirs below normal
Warning	Large index reservoirs below normal
Emergency	Continuation of previous months conditions

Water Requirement Satisfaction Index (WRSI) is an indicator of crop performance based on the availability of water to the crop during a growing season. It is based on the water supply and demand crop experiences during a growing season. It is calculated as the ratio of seasonal Actual Evapotranspiration (AET) to the seasonal crop water requirement (WR):

$$\mathrm{WRSI} = (\mathrm{AET}/\mathrm{WR}) \times 100$$

where WR is calculated from the Penman-Monteith potential evapotranspiration (PET) using the crop coefficient (Kc) to adjust for the growth stage of the crop:

$$\mathrm{WR} = \mathrm{PET} \times \mathrm{KC}$$

AET represents the actual amount of water withdrawn from the soil water reservoir (“bucket”). Whenever the soil water content is above the maximum allowable depletion (MAD) level (based on crop type), the AET will remain the same as WR, i.e., no water stress. But when the soil water level is below the MAD level, the AET will be lower than WR in proportion to the remaining soil water content.

The soil water content is obtained through a simple mass balance equation where the level of soil water is monitored in a bucket defined by the water holding capacity (WHC) of the soil and the crop root depth, i.e.,

$$\mathrm{SW}_i = \mathrm{SW}_{i-1} + \mathrm{PPT}_i - \mathrm{AET}_i$$

where SW is soil water content, PPT is precipitation, and *i* is the time step index.

The most important inputs to the model are precipitation and potential evapotranspiration (PET). It calculates daily PET values for Central America at 1.0-degree resolution from 6-hourly numerical meteorological model output using the Penman-Monteith equation. The Interpolated rain gauge data for Central America are obtained from NOAA at 0.1-degree (~10 km) spatial resolution. In addition, the WRSI model uses relevant soil information from the FAO (1988) digital soils map and topographical parameters from Digital Elevation Model (DEM) derived data (HYDRO-1K).

It requires a start-of-season time (SOS) and end-of-season time (EOS) for each modelling grid-cell. Maps of these two variables are particularly useful in defining the spatial variation of the timing of the growing season and, consequently, the crop coefficient function, which defines the crop water use pattern of crops. The model determines the SOS using onset-of-rains based on simple precipitation accounting. The onset-of-rains is determined using a threshold amount and distribution of rainfall received in three consecutive decades. SOS is established when there is at least 25 mm of rainfall in one decade followed by a total of at least 20 mm of rainfall in the next two consecutive decades. The length of growing period (LGP) for each pixel is determined by the crop variety. Generally, maize (corn) or beans with defined LGP are modelled for Central America.

At the end of the crop growth cycle, or up to a certain decade in the cycle, the sum of total AET and total WR are used to calculate WRSI in a Geographic Information System (GIS) environment at 0.1 degree (about 10 km) spatial resolution. A case of "no deficit" will result in a WRSI value of 100, which corresponds to the absence of yield reduction related to water deficit. A seasonal WRSI value less than 50 is regarded as a crop failure condition. As a monitoring tool, the crop performance indicator can be assessed at the end of every 10-day period during the growing season. As an early warning tool, end-of-season crop performance can be estimated using long-term average meteorological data. The spatially explicit water requirement satisfaction index (WRSI) studies have shown that WRSI can be related to crop production using a linear yield-reduction function specific to a crop. WRSI value is based on the actual estimates of meteorological data to-date. For example, if the cumulative crop water requirement up to this period was 200 mm and only 180 mm was supplied in the form of rainfall, the crop experienced a deficit of 20 mm during the period and thus the WRSI value will be [(180/200) × 100 = 90.0 %)].

Current WRSI can increase in value in the later part of the growing season if the demand (crop water requirement) and supply (rainfall) relationship becomes favourable. *Extended WRSI* is a forecast estimate of WRSI at the end of the growing season. Long-term average climatological data are used to calculate WRSI for the period between the current decade and the end-of-season. The calculation principles are the same as the "Current WRSI". This is also a deficit-based estimate of WRSI.

Water Requirement Satisfaction Index Anomaly maps show the relative magnitude of the WRSI as a percentage of the median WRSI:

$$\text{WRSI Anomaly (\%)} = (\text{Current WRSI/Median WRSI}) \times 100$$

where "Current WRSI" is actually the current WRSI that is extended to the end of season, and "Median WRSI" is WRSI generated using the median rainfall and evapotranspiration data from International Water Management Institute's data set (1961-1990). Although site/region specific validation is important, the user may use this anomaly map as a semi-quantitative indicator of the performance of the crops in relation to the average condition. For example, a value close to 100 signifies that this year's crop performance is about average, while percentage above and below 100 may indicate above and below average production forecasts, respectively.

5.5 Agricultural Indicators

Agricultural crops are sensitive to soil moisture. Drought index for agriculture requires proper consideration of vegetation type, crop growth and root development, soil properties, antecedent soil moisture condition, evapotranspiration and temperature. Some of the existing drought indices in use do not give proper consideration. Crop-Specific Drought Index (CSDI) takes into account the water use during specific periods of crop growth using a water balance model at the spatial scale. Diversification of crops irrespective of land-weather suitability and availability of water is on the increase leading to crop production below the expectation of the farmers. This leads to various social and economical constraints and problem for the family and states in general. In the process, valuable fresh water resources are non-effectively used or wasted. Hence, there is a need to disseminate information that would help the farmers in their knowledge drive decision. Drought indices are very useful monitoring tools, but they usually fall short in drought vulnerability studies as they are based on weather and short-term climatology. These indices do not take into account spatially variable crop water requirements, which are important determinants of agricultural drought vulnerability. Agricultural drought vulnerability largely depends on climatology, land use (e.g. crop composition), and soil water-holding capacity.

Recently, cultivation of crop is driven by economic considerations and farmer's decision making process needs quantitative information on crop-weather related parameters such as (1) water requirements for crop potential production, (2) water balance/availability that limits production, and (3) pest-disease-weather that reduce production, in selecting the crop type. In addition to the above information, length of the growing season, rainfall, drought probability, sunshine etc., anticipated to prevail during the period would help him in deciding the crop. Climate probability, risk of water deficiency, existing water use efficiency and irrigation type and schedule would help in the planning of irrigation system in achieving optimum crop production. In the past, drought intensity was most often measured via the departure of a climatic variable from normal and is closely linked to duration in determination of the impact. This method was limited in its ability to accurately characterize an event due to dependence on the 'average season' and assumes that seasonal climate in the region follows a normal distribution, which is rarely the case. Frequency of dry-day sequence as a measure of agricultural drought depends on the length of the sequence in combination with water content and water holding capacity of the soil and the water-use pattern of the crop. Agriculture drought exists as a result of the depletion of soil moisture in the root zone. Days with less than a certain threshold precipitation of 0.25 inches are considered as dry days.

The agriculture characterization may be presented on the basis of (a) administrative boundary (relevant decisions) and (b) classification of the main agricultural crops cultivated in the area of interest (differences from agro-climatic point. Agriculture drought characterization can be done by:

collection of daily historical meteorological data (at least 30 years), defining the growing season for individual crops and region, calculation of ratio between the total amount of rainfall for the growing period of each year and its mean value for the period considered, calculation of ratio between the longest time period with daily rainfall <5 mm for the growing period of each year and its mean $r_i = m_i/M$, where m is the maximum number of consecutive days in a year i and M is the average of m_i over the period. Calculation of the ratio between the total number of days with rainfall <5 mm for the growing period of each and its mean value $s_i = t_i/T$ where t_i is the total number of days in a year i and T is the average of t_i over the period considered and calculation of the ratio between total number of days in which Sum ETP > Sum Rainfall and its mean values for the period considered. ETP and Rainfall Sums for each year are relative to cumulated values starting at the beginning of the growing period (Maracchi G., 2000). The simple calculations are based on the necessity to relate the growing period to the main crops of the region, the combination of the total amount of rainfall with its distribution, the water balance trend during the growing season and normalization of all the values with respect to mean value of the whole period considered. The said analysis should underline the change in climatic patterns from which it is possible to derive the effect on the productivity of each in terms of quality and quantity.

Versatile Soil Moisture Budget (VSMB) model calculates the soil water balance within the rooting depth of the crop from precipitation, evapotranspiration and deep drainage data (Akinremi et al., 1996) Water is withdrawn simultaneously, but at different rates, from different zones (depths) in the soil profile, depending on the rate of potential evapotranspiration, the stage of crop development, the water release characteristic of the soil and the available water content of the soil.

Agrohydropotential (AHP) expresses the water requirement covering ability of a given field for any crop. It is the ratio between actual water consumption and the optimal water requirement of a crop and is crop specific.

$$\text{AHP} = W_t/W_r$$

where W_t is the actual water consumption; the actual evapotranspiration limited by the water balance and W_r is the water requirement, quasi optimal, unlimited evapotranspiration. AHP may vary between 1 and 0 indicating the degree of drought. This would help in the preparation of drought prognoses for any crop and also estimate the degree of drought susceptibility by the frequency of occurrence (Petrasovits, 1990).

Palmers' Z-index is the most appropriate indicator of agriculture drought. Z-index is derived from using soil moisture/water balance algorithm that requires a time series of monthly air temperature and precipitation data and information on the maximum soil water holding capacity (MSWHC) in the root zone. This index is a measure of the monthly moisture anomaly and reflects the departure of moisture conditions in a particular month from normal (or climatically appropriate) moisture conditions and it could be used on monthly or seasonal basis. Normally it is interpolated based on the network of weather stations.

Index of Moisture Adequacy (IMA) is a ratio of actual to potential evapotranspiration during the crop growth period (Sastri et al., 1981). *Soil Moisture Deficit Index (SMDI)* – Available soil water in the root zone was average over a seven-day period to get weekly soil water for each of the 52 weeks in a year. Median of the long-term soil moisture for 52 weeks of a year was chosen as a measure of normal available soil water (Narasimhan and Srinivasan, 2005). The maximum and minimum soil water for each week was also obtained. Using long-term median, maximum and minimum soil water, weekly percentage soil moisture deficit was calculated as:

$$SD_{i,j} = (SW_{i,j} - MSW_j/MSW_j - \min SW_j) \times 100 \qquad \text{if } SW_{i,j} = MSW_j$$

$$SD_{i,j} = (SW_{i,j} - MSW_j/\max SW_j - MSW_j) \times 100 \qquad \text{if } SW_{\ i,j} > MSW_j$$

where $SD_{i,j}$ is the soil water deficit (%), $SW_{i,j}$ mean weekly soil water available in the soil profile (mm), MSW_j the long-term median available soil water in the soil profile (mm), min SW_j and max. SW_j the long-term minimum and maximum available soil water respectively in the soil profile in mm (i = number of years, j = 52 weeks).

$$SMDI_j = (\Sigma^j{}_{t=1}\ SD_t)/(25t + 25)$$

SD value during any week gives the dryness (wetness) during that week when compared across season. SMDI during any week will range from –4 to +4 representing wet and dry conditions. It is computed at four different levels, using soil water available in the entire soil profile, then soil water available at top 2, 4, and 6 ft and are represented as SMDI, SMDI-2, SMDI-4 and SMDI-6 respectively in representing the potential crop to extract water from depths during different stages of crop growth and crop type.

Evapotranspiration Deficit Index (ETDI) – Daily model output of actual evapotranspiration and reference crop evopotranspiration were cumulated over a seven-day period to get weekly actual and reference crop evapotransiration for each of the 52 weeks in a year (Narasimhan and Srinivasan, 2005). Water stress ratio for the week is calculated as

$$WS = (PET - AET)/PET$$

WS is the weekly water stress ratio, PET the weekly reference crop evapotranspiration and AET, the weekly actual evapotranspiration. WS ranges from 1 to 0 indicating no evapotranspiration as 1 and 0 indicating the evapotranspiration occurring at the same rate as reference crop ET.

The long-term water stress for each week in a year was obtained by taking the median of the water stress for that week during 70 years period. The maximum and minimum water stress ratio for each week was also obtained. Water Stress Anomaly (WSA) was calculated as

$$WSA_{i,j} = (MWS_j - WS_{i,j}/MWS_j - \min WS_j) \times 100 \quad \text{if } WS_{i,j} = MWS_j$$

$$WSA_{i,j} = (MWS_j - WS_{i,j}/\max WS_j - MWSW_j) \times 100 \quad \text{if } WS_{i,j} > MSW_j$$

$WSA_{i,j}$ is weekly water stress anomaly, MWS_j the long term median water stress of week j, min and max WS_i minimum and maximum water stress of week j respectively and WS is the weekly water stress ratio (i = number of years and j = 52 weeks).

Water stress anomaly during any week ranges from –100 to +100 representing very dry to very wet conditions with respect to evapotranspiration.

$$ETDI_j = (0.5\ ETDI_{j-1}) + WSAj/50$$

Normalized Difference in Vegetation Index (NDVI) – Chlorophyll and carotenoid pigments in plant tissues absorb light in the visible red, while mesophyll tissue reflects light in the near-infrared wavelengths (Tucker and Sellers, 1986). A healthy and actively photosynthesizing plant will therefore look darker in the visible and brighter in the IR region than an unhealthy or dead plant. Normalized Difference Vegetation Index (NDVI) products are using measurements from the Advanced Very High Resolution Radiometer (AVHRR) on board the USA's NOAA polar orbiting meteorological satellites. The reflectance measured from AVHRR Channel 1 (visible: 0.58-0.68 microns) and Channel 2 (near-infrared: 0.725-1.0 microns) are used to calculate the index:

$$NDVI = (Ch2 - Ch1)/(Ch2 + Ch1)$$

The differential reflectance in these bands provides a means of monitoring density and vigour of green vegetation growth. Green leaves commonly have larger reflectance in the near-infrared than in the visible range. As the leaves come under water stress, become diseased or die back, they become more yellow and reflect significantly less in the near-infrared range. Clouds, water, and snow have larger reflectance in the visible than in the near-infrared while the difference is almost zero for rock and bare soil. Vegetation NDVI typically ranges from 0.1 to 0.6, with higher values associated with greater density and greenness of the plant canopy. Surrounding soil and rock values are close to zero while the differential for water bodies such as rivers and dams have the opposite trend to vegetation and the index is negative. A range of errors such as scattering by dust and aerosols, Rayleigh scattering, sub-pixel-sized clouds, plus large solar zenith angles and large scan angles all act to increase Ch1 with respect to Ch2 and reduce the computed NDVI. It ranges between –1 and +1 indicating non-healthy and healthy plants. It is highly useful in areas of sparse vegetation coverage, where they have a better range. A small index value corresponds to areas having minimal evapotranspiration that represents bare ground or little vegetation, relatively impermeable soils and minimal soil moisture. NDVI data can be analyzed to provide an indication of how plant growth in one season compares to the mean (or maximum) of many seasons, looking for divergence from the long-term mean or maximum. Another technique is to look at plant response over time, using accumulated NDVI images (namely two weeks); this provides an indication of relative change and patterns of change without requiring absolute calibration.

Monthly Vegetation Condition Index (MVCI) is prepared by temporal analysis of vegetation cover as,

$$\mathrm{MCVI_{j\ Jan} = (NDVI_{j\ Jan} - NDVI_{min\ Jan})/(NDVI_{max,\ Jan} - NDVI_{min\ Jan})}$$

where $\mathrm{MCVI_{j\ Jan}}$ is the image of monthly vegetation condition index value for data *j*, $\mathrm{NDVI_{j\ Jan}}$ is the image of NDVI value for *j*th image in January, $\mathrm{NDVI_{max,\ Jan}}$ and $\mathrm{NDVI_{min\ Jan}}$ are the minimum and maximum value record in the past January months.

Ground resolution of the sensors in satellite and their path over the study area are important in using this data. The sub-windowed information of interest such as the vegetation vigour of cropped area or natural vegetation would enhance the precision of ground-based reality. Natural vegetation has the ability to withstand water stress for longer periods. Image corresponding to different seasons were obtained in understanding crop vigour status. NDVI indices with observed physical conditions were used in the water stress evaluation.

Crop Moisture Index (CMI) reflects moisture supply in the short term across major-crop producing regions and is not intended to assess long-term drought. It identifies potential areas for agricultural droughts. CMI defines drought in terms of the magnitude of computed abnormal ET deficit which is the difference between actual and expected weekly ET. The expected weekly ET is the normal value adjusted up or down according to the departure of the week's temperature from normal. It is a location-based estimate and differs from place to place indicating the moisture condition. As it is designed for short-term soil moisture demand of the crops, it is not effective for long-term drought monitoring. It is not useful for crop initiation periods when it differs from place/plot to place-seed germination. It uses a meteorological approach to monitor week-to-week crop conditions and evaluate moisture conditions across major crop producing regions. It responds rapidly to changing conditions and location and time. It may not be applicable during seed germination or specific crop growing season. The continuous soil moisture measurement using tensimeter is essential in monitoring agriculture drought. Water deficit affects crop growth and development, directly or indirectly. Crop water status is highly dynamic and influenced by soil and atmospheric microenvironment and regulated by physiological factors of species. The crop may be tolerant for moderate drought at flowering stage, and the yield reduction would result in decline in crop yield, when the drought is prevalent during anthesis and grain filling stage (Krishnan, 1979). The water stress on a plant is assessed by measurement of leaf water potential, concentration of leaf sap, leaf turgidity and stomatal aperture. The stiffness of leaves indicates water stress and the crop growth will be ceased prior to wilting of leaves.

Measurement of soil moisture or determination of evapotranspiration is useful. Estimation of potential evapotranspiration and water budgeting approach would also indicate water stress. The actual evapotranspiration is considerably influenced by soil water supply, plant structure and physiological conditions of leaf and rooting depth etc. If the surface is wet immediately after irrigation, then the rate of evaporation is almost the same as an exposed water surface receiving the same amount of net radiation. If it is dried, evaporation takes place from the deeper layers of soil. There is a sharp and continuous decline depending on the length and complexity of internal diffusion pathway within the soil. The availability of soil moisture to plants from the field capacity to permanent wilting percentage determines the nature of soil drying rate. Linear and exponential (Lemon, 1968) relationship exists between relative transpiration rate and available soil water. The moisture loss proceeds at the potential rate as long as moisture is available at plant roots and the transpiration rate declines, when the soil begins to dry. These drying curves are exponential. The third stage is the moisture loss by vapour diffusion that takes place from dry layers of soil.

A majority of the indices are not used to determine an end of a drought because many of the indices will tend to return to normal at some point during the year. For example, the Crop Moisture Index returns to normal at the end of the growing season. In addition the end of a drought is easily defined by rainfall and groundwater levels, which have the most significant impact on the other indices.

5.6 Sociological Indicators

Social impacts mainly involve public safety, health, and conflict between water users, reduced quality of life and inequalities in the distribution of disaster relief. Population out-migration is a significant problem in many countries. Deaths resulting from famine are sometimes mistakenly attributed to drought rather than underlying causes such as war or civil strife. Environmental losses are the damages to plant and animal species, wildlife habitat and air and water quality, forest and range fires, degradation of landscape quality, loss of bio-diversity and soil erosion. Some of them are short-term and conditions quickly return to normal following the end of the drought. These losses are difficult to quantify. Economic losses occur in agriculture and related sectors, including forestry and fisheries. The obvious losses in yields in crop and livestock production due to drought is associated with increases in insect infestation, plant disease and wind erosion. Table 5.1 shows the parameters that are assessed in establishing socio-economic drought.

Table 5.1: Agro-meteorology drought indicators (WMO, 1975)

Author	*Definition and concept*	*Country*
Water, Moisture		
Fitzpatrick (1965)	A water use model with range of available soil moisture 0–10 cm and evapotranspiration losses (E_t) computed from Australian sunken evaporimeter (E_A) $E_t = 0.8\ E_A$ when soil moisture >64 mm $E_t = 0.4\ E_A$ when soil moisture <64 mm	Australia Used in climatic studies and land-use surveys
Van Bavel & Verlinden (1956)	A day on which the available soil moisture was depleted to some small percentage of available capacity	
Thornwaite & Mather (1955)	Used the water-balance concept with variable storage of soil water	USA. Use extended to other continents. Some results are doubtful
Fitzpatrick (1965)	Water-use model with a range of available soil moisture 0-10 cm and evapotranspiration losses (E_t)	Australia Climatic studies and land-use survey
Precipitation, Temperature Aridity		
Abuz Zeid & Abdel Dayem (1990)	Use the first year's moving average of annual rainfall	
Baldwin-Wiseman (1941)	Engineers drought in Australia is three or more consecutive monthly with deficit of 50% from mean rainfall	Australia
Banerjee & Chabra (1964)	A seasonal rainfall deficit of more than 50% is considered as a severe drought	Andhra Pradesh, India
Bates (1935)	Annual precipitation is 75% of normal or monthly precipitation is 60% of normal	USA
Bazza & Stockton (1990)	Use the coefficients of variation of annual and monthly precipitation	
Blumenastock (1942)	A period with precipitation less than some small amount such as 0.10 inches in 48 hours	

(*Contd.*)

Table 5.1 (*Contd.*)

Author	*Definition and concept*	*Country*
Bova (1941)	Drought index $K = 10(H+Q)/\Sigma_t$ where H is productive soil moisture in mm in the top 100 cms of soil at beginning of spring; Q is precipitation in mm accumulated daily from start of spring; Σ_t is the temperature in (°C) counted from the day of the passage of mean daily temperature through zero	USSR When $K \leq 1.5$ start of drought damage to plants is indicated
British Rainfall Organisation (1936)	Absolute drought – at least 15 consecutive days none of which receive as much as 0.25 mm Partial drought – at least 29 days during mean rainfall does not exceed 0.25 mm/day Dry spell – at least 15 consecutive days none of which has received as much as 1 mm.	Britain Inapt in drier region
Brounove	Ten days with rainfall not exceeding 5 mm	
Bryant et al. (1992)	Drought Severity Index (DSI) is the accumulated monthly deficit relative to the mean for a standard period (say 1951 - 1989)	
Clarke (1991)	Annual rainfall <75% of the average is regarded as a drought	
Cole (1933)	15 days with no rain	USA
Condra (1944)	A period of strong wind, low precipitation, high temperature and unusually low relative humidity	USA
De Martonne (1926)	Index of aridity I = Mean Annual Precipitation/(Mean Annual Temperature +10)	Used extensively by geographers and biologists to define aridity. Used to define climatic limits of deserts, prairies and forest. Does not apply well in cool zones where T+10 approaches to zero
Emberger (1955)	$t = 100\ p/(M-m)(M+m)$ where M is the mean maximum temperature in the hottest month and m is the mean minimum temperature in the coldest month; p in mm and M in °C.	France Based on De Martonn'es Index (M–m) is an index of continentality

(*Contd.*)

Fitzpatrick (1953)	Period terminated by at least 6.4 mm during any 48 hours	Australia Evaluated probability that dry spells of any length would occur at any time throughout the year
Foley (1957)	Computed residual mass curves of rainfall. Divided values by average annual rainfall to give index of severity	Australia Dividing by annual average makes comparison between more reliable stations. Index is dimensionless
Garrido (1998)	Normalized Precipitation Index (NPI) combination of PDSI and SPI	Spain (UE) a drought watch for southeast Spain
Gaussen (1954)	When total monthly precipitation in mm is less than twice the mean temperature in °C.	An approximation to rainfall lower than evapotranspiration
Gibbs & Maher (1967)	Rainfall deciles to demonstrate temporal and spatial distribution of drought. Areas where rainfall is included in the first decile (10% of normal precipitation of the period) coincide with drought areas	Australia Provides a useful presentation of spatial distribution of drought
Gommes & Petrassi (1994)	National Rainfall Index (RI) is calculated for each country by taking a national average of annual precipitation weighed according to the long term precipitation averages of all the individual stations	Africa RI allows comparison to be made between years and between countries
Hargreaves (1974; 1988)	Compares rainfall with Moisture Availability Index (MAI)	South America and Africa. It defines a series of thresholds to classify water available for crops
Henry (1906)	21 days or more when rainfall is 30% or less of average for the time and place. Extreme drought where rainfall fails to reach 10% of normal for 21 days or more	USA
Hoyt (1936)	Any amount of rainfall <85% of normal	USA
Karl & Knight (1985)	PHDSI – hydrological drought index based on precipitation, outflow and storage. Does not take into account long term trends	USA It is an evolution of the PDSI, able to operate in near real time
Knochenbauer (1937)	Daily max. temperature and humidity (measured in the afternoon) used to define a dry spell	Germany

(*Contd.*)

Table 5.1 (*Contd.*)

Author	*Definition and concept*	*Country*
Koloskov (1925)	Ratio of annual precipitation and accumulated mean daily temperature during the vegetation period (divided by 100)	USSR Ratio may be used as comparative agro-climatic index
Koppen (1931)	Dry climate – where $p<2t$ for regions of winter rains and $p<2t+14$ for regions of summer rains or no rainy season, where p is annual precipitation in cm and t is mean temperature in °C. Desert climate – where $p<2t$ for regions of winter rains and $p<2t+14$ for regions of summer rains; $p<2t+7$ no rainy season	Used extensively in classification of the dry climates of the world
Kulik (1958)	Uses preceding meteorological conditions, soil characteristics and level of agronomic techniques in the region. Semi-drought - 10 days with soil water 20 mm in first 20 cm of soil. Drought as above with 10 mm of water	USSR
Kulshreshtha & Klein (1920)	Use a comparison of annual time series of precipitation and wheat yields	
Lang (1915)	Precipitation factor I = Mean Annual Precipitation/Mean Annual Temperature	Germany Used for climatic classification soils. When I is lower than 40 the soil is arid
Le Houerou (1988)	Dependable rains (DR) based on the concept of dependable rains, defined as the amount of rainfall that occurs in four years of five-year period	Africa It is used to realize plans for agricultural productions
Le Houerou & Popv (1981)	Use a ratio between rainfall and potential evapotranspiration	Africa uses a series of thresholds to classify the rainy season
Phillips & McGregor (1998)	DSI3 – Three months Drought Severity Index – drought starts when the rainfall of a month is lower than the mean of the last three monthly mean DSI6 – Six months Drought Severity Index – based on the previous one to test the sensitivity/stability of DSI3.	Great Britain Used to assess drought hazard in England
Popov (1948)	Index of aridity $P = \Sigma_g /(2.4\ (t\text{-}t)r$ where Σ_g is annual amount of effective precipitation; t-t is annual mean wet bulb depression °C; r is factor depending on day length; and g is that part of precipitation which is available for planners	

(*Contd.*)

Ramdass (1950)	When actual rainfall for a week is half of normal or less	India
Selyaninov (1930)	$k = \Sigma_p /\Sigma_t/10$, where p is sum of rainfall (mm) during those months when mean temperature is above 10 °C and t is the sum of daily mean temperatures above 0 °C for the same period	USSR A period be considered as a dry spell when $k < 1$ and as a drought when $k < 0.5$
Selyaniov (1930)	Index of aridity	USSR Dry spell when aridity is <1 and drought when it is <0.5
Tannehill (1947)	A period of 21 days when rainfall is 30% less than normal for the place and time	
Tardie & Plus (1990)	Use three years moving average annual rainfall	
Tennessee Valley Authority (1944)	When no interval of 21 consecutive days received precipitation $> {}^{1}/_{3}$ of normal	
Moisture and Crop		
Barger & Thorn (1949)	Evaluated precipitation climate from productive performance of crops	USA
White (1955)	With respect to xerophilous species using comments on pasture conditions as guide	Western NSW Australia Extrapolation to other areas not reliable
Alpat'eve & Ivanova (1958)	Definition of severity on the comparison of crop yields with long-term mean yields. Not all yield decreases are as a result of drought. When yield decreases by 25% it is classified as drought	Variations in yield due to different levels of agronomic practices are still greater than those due to drought (Kulik, 1958)
Mcroy (1968)	Introduces variable to consider leaf wetness and improve aerodynamic function	Australia uses for conditions of limited soil moisture but measurement of any parameters restricts wide application
Holmes (1962)	Quantitative evaluation of drought for agriculture purpose. Precise and regular soil-water observations are essential	Canada
Rickard (1966)	Agriculture drought exists when soil water in the root zone is at or below the permanent wilting percentage. The condition continues until	New Zealand Drought relief would not occur if one day excess rainfall

(*Contd.*)

Table 5.1 (*Contd.*)

Author	*Definition and concept*	*Country*
	rainfall in excess of daily evapotranspiration	threshold
Rickard (1966)	Agriculture drought exists when the soil water in the root zone is at or below the permanent wilting percentage. The condition continues until rain fall in excess of daily ET	New Zealand Drought relief would not occur with one day of excess rainfall (2.5-5 mm)
Ross (1990)	When the crop moisture demand exceeds soil moisture and the system ability to supply	Lehbridge Northern Irrigation district, Alberta
Shafer & Dezman (1982)	Surface water supply index (SWSI). It is designed to be an indicator of surface water condition and described as mountain water dependent in which mountain snowpack is a major component.	Colorado USA It is modified and applied in other western states – Oregon, Montana, Idaho and Utah
Sly (1970)	Climate moisture index	Canada – average seasonal values indicating differences in water balance used for soil climate classification purpose

Source: Tate et al., 2000

Human vulnerability is defined as human condition or process resulting from physical, social, economic and environmental factors that determine the likelihood and scale of damage from the impact of a given hazard. *Risk* can be expressed by the number of people killed or made to suffer, as compared to exposed population. *Elements at risk* is an inventory of those people or artefacts that are exposed to the hazard. The socio-economic vulnerability indicators (UNDP/UNEP/WMO) are shown in Table 5.2.

Falkenmark Water Stress Indicator is based on the estimation that a flow unit of one million cubic metres of water can support 2000 people in a society with high level of development, using 1700 m^3/capita/year, is defined as the threshold above which water shortage occurs only irregularly or locally. Below this level water scarcity occurs in different levels of severity. Below 1700 m^3/capita/year water stress appears regularly; below 1000 m^3/capita/year water scarcity is a limitation to economic development and human health and well-being and below 500 m^3/capita/year water availability is a main constraint to life. Constraints are – only the renewable surface and groundwater flows in a country being considered. Water availability per person is calculated as an average with regard to both the temporal and

Table 5.2: Socio-economic vulnerability indicators

Category	*Indicators*
Economic	Gross Domestic Product per inhabitant @ purchasing capacity Human Poverty Index (HPI) Total debt service Inflation, food prices (Annual %) Unemployment (% total labour force)
Type of economic activities	Arable land (in hectare) % of arable land and permanent crops % of urban population % of agriculture dependency % of agriculture's dependency for GDP % of labour force in agriculture sector
Dependency and quality of environment	Forest and woodland (% in total area) Human induced soil degradation
Demography	Population Urban growth Population density Age dependency ratio
Health and Sanitation	% of people access to clean water, sanitation Number of physician (per 1000 habitants) Mortality rate at birth Life expectancy Number of beds in hospital
Early warning system	Number of radio
Education	Literacy rate
Development	Human Development Index

spatial scale and thereby neglects water shortages in dry seasons or in certain regions within a country.

Climate Vulnerability Index (CVI) links climate variability and change, water availability, and socio-economic factors from community to national and regional levels (Sullivan and Meigh, 2005). The assessment of risk in relation to water resources is strongly dependent on people's vulnerability to water-related hazards. The CVI identifies a range of social, economic, environmental and physical factors relevant to vulnerability and incorporates them into an integrated index. Based on a series of subcomponents, the six major components are combined using a composite index approach (similar to the HDI). The resulting scores range on a scale from 0 to 100, where 100 represents the highest level of vulnerability. It systematically expresses the human vulnerability in relation to water resources, both for current conditions and for future scenarios. It can therefore help risk managers and water managers develop a warning system for water scarcity and possible drought events.

5.7 Environmental Indicators

They are: (1) Land use consistent with *agricultural suitability* and agricultural capability. Trends in land use agricultural suitability and capability maps showing land inappropriately used for agriculture, or used beyond its capability as agricultural land, is an indicator of unsustainable development. (2) Changes in *long-term net real farm income*. (3) Profitable agriculture should not be at the expense of the environment, and it should be recognized that gains might be made by preventing or repairing land degradation. Other factors, such as terms of trade and new technologies, also need to be recognized. (4) *Changes in the quality of land and water* – Rate of soil loss per tonne of product, water balance/efficiency, nutrient balance and cycling. (5) *Condition of pasture area* of native vegetation and degree of fragmentation. This indicator represents on-site environmental effects. It is possible to define the optimal state of health of the natural resource base (land, soil and water), to define the critical tolerances for most domesticated plant and animal species. (6) Changes in the *level of managerial skills* of land managers. State of development of land and water management plans. (7) *Land care attitude index* – Catchment management and farm planning capacity. The increase in managerial skills and attitudes to stewardship can improve on-site environmental management. (8) Changes to product quality, hydrology and native ecosystems attributable to agricultural practice. Ground and surface water quality. Chemical contaminants of agricultural products, length of contact zone with non-agricultural areas. *Environmental Sustainability Index*.

Category	*Indicator*
Resource depletion	Water consumption Inputs of phosphate to agricultural land
Dispersion of toxic substances	Index of heavy metal emissions to water Emissions of persistent organic pollutants (POPs) Consumption of toxic chemical
Water pollution	Emissions of nutrients by households Emissions of nutrients by industry Pesticides used per hectare of utilized agriculture area Nitrogen quantity used per hectare of utilized agriculture area Emissions of organic matter from households Emissions of organic matter from industry Non-treated urban waste water
Urban environmental problems	Non-treated wastewater
Marine environment and coastal zones	Tourism intensity

Drought indices that are described above are inherently complex due to the multiple causes, processes and impacts of drought. The difficulty of obtaining relevant data series and, more importantly, of modelling the interactions between natural processes and human responses, typically leads to drought assessments being oversimplified. Drought watch maps and information are issued at regular intervals for the public as well official's awareness.

5.8 Indicators and Triggers

As shown in preceding section drought may be characterized in many different ways, because single indicator often proves inadequate for decision making process and multiple indicators are useful. But challenges arise in trying to combine multiple variables and values in a drought management plan. Indicator scales may be incomparable, and trigger values may be statistically inconsistent. Comparison of the three index scales above illustrates common problems with indicators and triggers in drought plans. These problems exist not only for values of indices (e.g., SPI, PDSI/PHDI, SWSI), but also for values of indicators (e.g., total monthly precipitation, average monthly stream flow, average monthly reservoir levels), for several reasons. Drought categories (levels) are inconsistent in terms of cumulative frequency. Index values are difficult to interpret directly and imply different probabilities of occurrence for different indicators. The values of the indicator can vary, in terms of frequencies, depending on time and location (with the exception of the SPI). Because of these inconsistencies and use, more than one indicator in operational drought management cause confusion and impede effective and timely drought response (Steinemann, Hayes and Cavalcanti, 2005).

A comparison of state drought plans adopted by countries show wide variation concerning indicators and triggers. A plan mentions indicators, but without details on how these indicators are measured or used. It provides partial guidance on indicators, but without information on trigger values and corresponding drought levels. It provides typically raw values of the indicators, which often lack statistical consistency. It contains details on indicators and trigger values, plus triggers and associated drought levels are statistically comparable. In order to solve the problem, the indicators and indices can be transformed to percentiles by fitting a distribution to the data (such as a Gamma distribution or Pearson III for precipitation), or by developing an empirical cumulative distribution function (ECDF) using ranking algorithms, plotting positions, or other cumulative probability estimators. The drought plan triggers are then based on percentiles instead of raw indicator or index values.

Drought triggers are threshold values of an indicator that distinguish a drought level, and determine when management actions should begin and end. Triggers ideally specify the indicator value, the time period, the spatial scale, the drought level, and whether progressing or receding conditions. Drought levels (phases, stages) are categories of drought, with nomenclature such as "mild, moderate, severe, extreme drought," or "stage 1, stage 2, stage 3 drought."

Based on a systematic review of state and local drought plans, and interviews with water officials, a set of considerations and criteria for indicators and triggers has been developed:

1. **Suitability for drought types of concern:** An indicator needs to reflect the type of drought of concern, including aspects of water demands, water supplies, drought vulnerabilities, and potential impacts. Because drought depends on numerous factors, no single indicator is likely to cover all types of drought.
2. **Data availability and consistency:** The performance of an indicator depends on the availability and quality of the data. Many indicators are conceptually attractive, but are difficult, costly, unreliable, or impractical to generate, so they may not be appropriate for use. Many drought plans use indicators based on data that are already collected, subjected to quality control, and consistently reported, such as by a government agency. Prior to choosing an indicator to be included for decision-making purposes, the conditions may be evaluated – Is the indicator straightforward to calculate? Are the data readily available? Are the data trustworthy? Will the analytic expense justify the decision-making value? Does the value of the indicator vary, depending on the source of data or method of calculation? Is there a consistent long-term record, and will the data be consistently generated in the future?
3. **Clarity and validity:** Indicators and triggers need to be readily understood and scientifically sound, so that drought decisions can be made and defended on the basis of them. In addition, they should be tested before a drought, and evaluated after a drought, to see how well they perform. A pre-drought assessment could involve generating historic sequences of triggers, and comparing them to human assessments of the drought triggers that should have been invoked during that time. Another approach is to conduct virtual drought exercises with stakeholders and decision makers, using different sets of triggers and comparing management responses. A post-drought evaluation could involve a similar process of comparing actual triggers invoked to triggers that would have provided the greatest decision-making value.
4. **Temporally and spatially sensitive:** Indicators and triggers need to consider both temporal and spatial variability. This is because of indicator levels that imply the drought conditions for one time for a region.

5. **Temporally and spatially specific:** Indicators and triggers also need to specify the temporal and spatial scale of analysis such as a climate division or hydrological basin for precipitation, soil moisture, and snow pack and parameters such as groundwater, reservoir levels/storage, and stream flows. Spatial scale may be implicitly defined by the selection of a specific well, reservoir, or gauging station. Indicators should, nevertheless, specify the spatial scale of drought that they seek to represent. Triggers need to define the spatial scale of implementation of drought responses, such as the use of three groundwater wells to trigger drought responses within an entire climate division or county. Even a trigger such as a reservoir level does not necessarily imply that the spatial scale of response is that reservoir, but instead could trigger responses, such as water use restrictions, for an entire state.
6. **Drought progressing and receding:** Indicators and triggers should be defined both for getting into a drought, and getting out of a drought, at each level of a drought plan. Even though many drought plans assume that the progressing triggers can be reversed to function as the receding triggers that may not be desirable from a drought management perspective. There may be different management goals for going into a drought versus going out of a drought. For instance, it may be important to implement water use restrictions as soon as drought conditions start developing, but to be more conservative and wait to lift restrictions when drought conditions appear to be recovering. Trigger examples would be to invoke a drought level after two consecutive months in a certain or more severe level, but to wait to revoke drought restrictions until after four consecutive months in a certain or less severe level.
7. **Statistical consistency:** Triggers need to be statistically consistent with drought levels, as well as with other triggers in a drought plan. As we saw earlier, the probabilities of occurrence of the Palmer Index were not consistent among drought levels, and varied according to time and locations. Moreover, the index scales of the PDSI/PHDI, SPI, and SWSI were not consistent with each other. For instance, the value of –1.5 had different cumulative frequencies for each index. From the perspective of a decision maker, the choice of drought indicators may be difficult, but that difficulty will be compounded if indicator scales and trigger values cannot be validly compared and combined in drought decision-making.
8. **Linked with drought management goals:** Indicators need to be linked with drought management and impact reduction goals, and trigger levels should be set to invoke responses at times and stages that are consistent with these goals. For instance, triggers can be set so that a certain percentile will invoke responses that will produce a desired percentage reduction in water use. Drought indicator performance should also be considered; for instance, the degree of responsiveness or persistence

desired in an indicator. Some water managers may prefer an indicator that responds quickly to short-term anomalies, such as the SPI-3, in order to take early action to reduce drought impacts, whereas other water managers may prefer an indicator with greater stability and persistence, such as the SPI-12, in order to avoid frequent invoking and revoking of drought responses. Intermediate indicators, such as the SPI-6, can provide elements of both.

9. **Explicit combination methods:** Drought plans often rely on multiple indicators. But a question arises: If multiple indicators are used, how are they considered or combined to determine a final drought level? In other words, multiple triggers may suggest different drought levels, so methods need to be specified for combining triggers and determining the final level. These can include quantitative methods and criteria such as: the most severe of the indicators, at least one of the indicators, or a majority of indicators. These can also include qualitative methods, such as convening a drought committee to determine when to implement responses. Whether quantitative or qualitative, the methods for calculating indicators should be specified, as well as the process for combining opinions or weighing individual data for an overall indicator.
10. **Quantitative and qualitative indicators:** Indicators can be based on quantitative data and qualitative assessments, or both. Although many drought plans centre on quantitative indicators, the importance of qualitative expertise should not be overlooked. A human expert is able to consider and synthesize numerous indicators, applying years of experience and expertise to assess drought conditions. Perhaps even more important is the recognition that indicators and triggers are meant to help decision makers, not replace decision makers. A drought plan is but one source of information, and other considerations will likely be important for decision making.

A large number of variables put together form the characteristic/defining features for the classification of a region that qualifies for drought-proofing interventions. Rarely does any one single variable capture the essential features of any such socio-economic phenomena, but more so for an exercise such as this, which strides economic, ecological, climatic, social and demographic features. Thus constructing a composite index may present a composite picture from properly chosen variables. The issues faced during compositing of variables are: (a) removing biasness of scale and (b) determination of weights for the variables. In regional analysis usage of different variables with varying units/scales of measure is a common problem. Thus the process of making the data scale-free is essential to make the indicators comparable. Standardisation changes simultaneously the origin as well as the scale of measurement. The mean of all the standardized variables are equal to zero and the standard deviation is equal to one. Thus by standardization we lose information on disparity, which exists between the variables. Under this method the matrix of the sum of squares and cross products becomes the correlation matrix of the original variable. In our analysis the standardization method for making the data scale-free, its set is carried out as in Principal Component Analysis (PCA). The biggest weakness of this method is its tendency to maximize weights on variables with maximum variance. Through standardization technique this factor will tend to be neutralised.

Thus the three main tasks in constructing a drought vulnerability index are identifying the variables, their standardization and assigning correct weights to them. While doing this, the interrelationship between variables must be kept in mind. This can be done with the help of the principal component analysis method of data reduction, the major problem of which is that it gives maximum weightage to those variables that have the highest variance. However, if care is exercised to ensure that the selection of variables is correct and the correlations within the selected group of variables are of the theoretically expected magnitude and direction, it is a very useful tool for constructing a composite index of this kind.

Continuous observations on the important parameters of crop growth and production have led to creation of indicators related to on-set/beginning of drought situation and normalcy. The observation platform ranges from the agriculture plots and village level and regional level using on-site observation posts and air-borne systems. Various satellite-based observation kits that are available for this purpose are discussed in the next chapter.

References

Gibbs, W.J. and Maher (1967). Rainfall deciles as drought indicators. *Bureau of Meteorology Bulletin*, **48**, Commonwealth of Australia, Australia.

James, E.J. (1999). Evapotranspiration losses with studies from Kerala. Proceedings International workshop on Water Surfaces. CBIP Publication no. 205, pp. 201-206.

Krishnan, A. (1979). Definition of droughts and factors affecting relevant to specifications of agricultural and hydrologic droughts. Proceedings International Symposium on Hydrological aspects of drought, 3-7 December 1979, New Delhi. pp. 67-102.

Lemon, E.R. and Sinn, J.H. (1968). Photosynthesis under field condition, Soil-Plant-Water relations during drought stress in corn. *Agronomy Journal*, **60**, pp. 337-343.

McKee, B., Doesken, N.J. and Kleist, N. (1993). The relationship of drought frequency and duration to time scales. Proceeding 8th Applied Meterology, 17-22 Jan, Anaheim, CA, pp. 179-184.

Narasimhan, B. and Srinivasan, R. (2005). Development and evaluation of Soil Moisture Deficit Index (SMDI) and Evapotranspiration Deficit Index (ETDI) for agriculture drought monitoring. *Agricultural and Forest Meteorology*, **133**, pp. 69-88.

Palmer, W.C. (1964). Meteorological drought. Usther Bureau, Department of Commerce Research paper 45, Washington DC.

Parthsarathy, B., Sontakke, N.A., Monot, A.A. and Kothawale, D.R. (1987). Droughts/floods in the summer monsoon season over different meteorological subdivisions of India for the period 1871-1984. *J. Climatology*, 7, pp. 57-70.

Petrasovits, I. (1990). General review on Drought strategies. *In:* Transactions of 14th Congress on Irrigation and Drainage, Rio De Janiero, Vol. 1-F International Commission on Irrigation and Drainage (ICID) G 43.1-43.27.

Rathore, L.S. and Biswas, B.C. (1999). Pan evaporation over India. Proceedings International workshop on Water Surfaces. CBIP Publication no. 205, pp. 61-68.

Salvati, L., Libertà, A. and Antonio Brunetti, A. (2005). Bio-climatic Evaluation of Drought Severity: A Computational Approach using Dry Spells. *Journal Ecology and Biology*.

Sastri, A.S.R.A.S., Ramakrishna, Y.S. and Ramana Rao, B.V. (1981). A new method of classifying agricultural drought. *Archiv fur Meterologies Geophysik und Bioklimatologie*, ser B.29, pp. 283-287.

Steinemann, A., Hayes, M.J. and Cavalcanti, L. (2005). Drought Indicators and Triggers. *In:* Wilhite, D. (ed.) *Drought and Water Crises: Science, Technology, and Management Issues*. Marcel Dekker, NY.

Thornwaite, C.W. and Mather, J.R. (1957). Instruction and table for computing potential evapo-transpiration and the water balance. *Climatology*, **10(3)**.

Tucker, C.J. and Sellers, P.J. (1986). Satellite remote sensing of primary production. *International J. Remote Sensing*, **7,** pp. 1395-1416.

Further Reading

Akinremi, O.O., McGinn, S.M. and Barr, A.G. (1996). Simulating soil moisture and other components of the hydrological cycle using a water budget approach. *Canadian Journal of Soil Science*, **75,** pp. 133-142.

Brunetti, M., Maugeri, M. and Nanni, T. (2001). Changes in total precipitation, rainy days and extreme events in northeastern Italy. *International Journal of Climatology*, **21**, pp. 861-871.

Brunetti, M., Maugeri, M., Nanni, T. and Navarra, A. (2002). Droughts and extreme events in regional daily Italian precipitation series. *Int. J. Climatol,* **22**, pp. 543-558.

Loaiciga, H.A. and Leipnik (1996). Stochastic renewal model of low-flow stream flow sequences. *Stochastic Hydrology and Hydraulics*, **10(1)**, pp. 65-85.

Lohani, V.K. and Loganathan, G.V. (1997). An early warning system for drought management using the Palmer Drought Severity Index. *Nordic Hydrology*, **29(1)**, pp. 21-40.

Maracchi, G. (2000). Agricultural drought – A practical approach to definition, assessment and mitigation strategies. *In:* Vogt, J.V. and Somma, F. (eds). Drought and Drought Mitigation in Europe. Kluwer Academic Publishers, pp. 63-75.

Sullivan, C.A. and Meigh, J.R. (2005). Targeting attention on local vulnerabilities using an integrated index approach: The example of the Climate Vulnerability Index. *Water Sciences and Technology* (Special Issue on Climate Change), **51(5),** pp. 69-78.

Tate, E.L. and Gustard, A. (2000). Drought definition: Hydrological perspective. *In:* Vogt, J.V. and Somma, F. (eds) Drought and Drought Mitigation in Europe. Kluwar Academic Publishers, pp. 23-48.

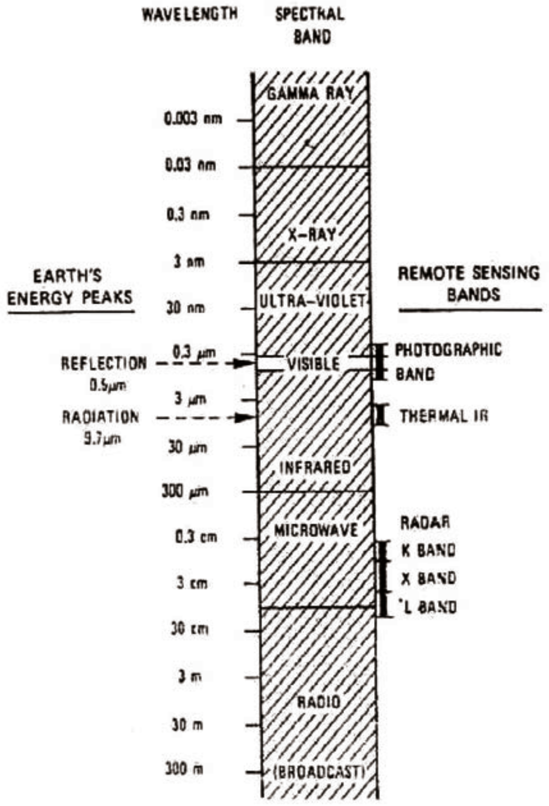
6

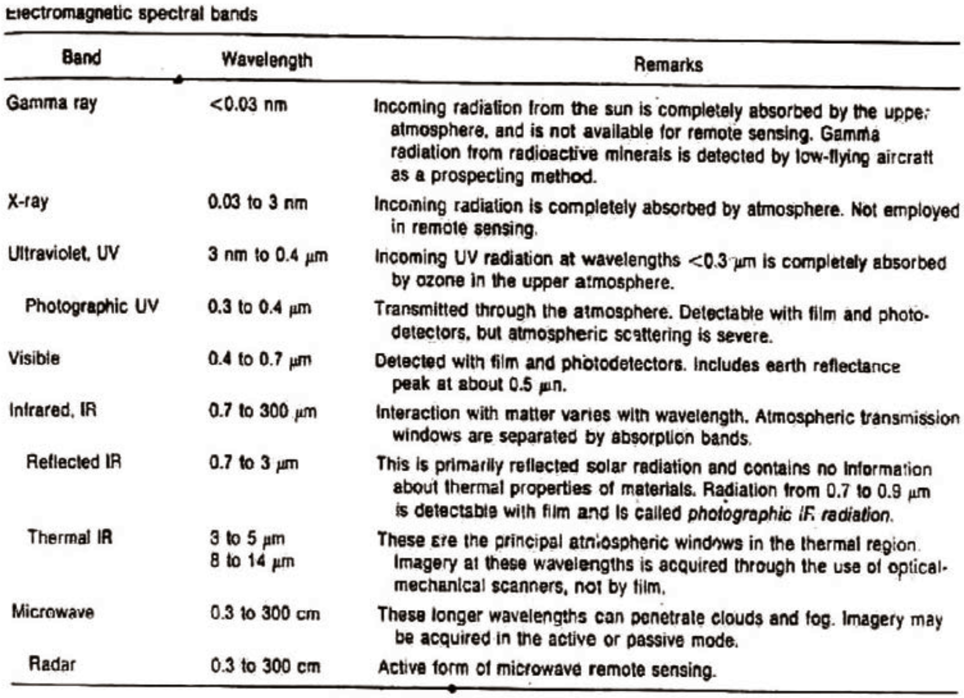
Satellite Remote Sensing

Accurate and reliable georeferenced information, early warning and alert message based on scientific monitoring techniques and methods would minimize the severity of the impending drought. Spatial and temporal co-ordinates and attributes would enhance the reliability and also, in communicating, the potential impact to the specific vulnerable groups of the society. The advancements made in the orbital resources satellite technology could aid in mapping the disaster area, prediction/forecasting of impending disaster and disaster relief management. They are discussed in this chapter.

6.1 Remote Sensing

Remote sensing is the science of obtaining information about an object, area or phenomenon through the analysis of data acquired by a device that is not in contact with the object under investigation. The remotely collected data can be of many forms including variations in force distribution, acoustic wave distributions or electromagnetic energy distributions. The electromagnetic energy sensors that are currently being operated from air-borne and space-borne platforms to assist in mapping and monitoring of earth resources are shown in Fig. 6.1. Remote sensing techniques take advantages of the unique interaction of radiation from the specific regions in the spectrum and the earth. The basic components are: (1) radiation source (sun, radar); (2) transmission path (atmosphere, vegetation canopy); (3) target (soil, water) and (4) sensors (multispectral scanner, photographic film etc.). Atmospheric gases such as N_2O, O_2 and O_3, CO_2 and H_2O absorb the sun's incident electromagnetic energy in the 0.1 to 30 μm (Fig. 6.2). *Gamma radiation* remote sensing is based on the attenuation of natural terrestrial gamma radiation by soil water or a layer of snow. *Aerial photographs* use the visible portion of the electromagnetic spectrum and also in near-infrared and thermal regions. Multispectral scanners measure the spectral reflectance





Electromagnetic spectral bands

Band	Wavelength	Remarks
Gamma ray	<0.03 nm	Incoming radiation from the sun is completely absorbed by the upper atmosphere, and is not available for remote sensing. Gamma radiation from radioactive minerals is detected by low-flying aircraft as a prospecting method.
X-ray	0.03 to 3 nm	Incoming radiation is completely absorbed by atmosphere. Not employed in remote sensing.
Ultraviolet, UV	3 nm to 0.4 μm	Incoming UV radiation at wavelengths <0.3 μm is completely absorbed by ozone in the upper atmosphere.
Photographic UV	0.3 to 0.4 μm	Transmitted through the atmosphere. Detectable with film and photodetectors, but atmospheric scattering is severe.
Visible	0.4 to 0.7 μm	Detected with film and photodetectors. Includes earth reflectance peak at about 0.5 μm.
Infrared, IR	0.7 to 300 μm	Interaction with matter varies with wavelength. Atmospheric transmission windows are separated by absorption bands.
Reflected IR	0.7 to 3 μm	This is primarily reflected solar radiation and contains no information about thermal properties of materials. Radiation from 0.7 to 0.9 μm is detectable with film and is called *photographic IR radiation*.
Thermal IR	3 to 5 μm 8 to 14 μm	These are the principal atmospheric windows in the thermal region. Imagery at these wavelengths is acquired through the use of optical-mechanical scanners, not by film.
Microwave	0.3 to 300 cm	These longer wavelengths can penetrate clouds and fog. Imagery may be acquired in the active or passive mode.
Radar	0.3 to 300 cm	Active form of microwave remote sensing.

Fig. 6.1: Electro-magnetic spectrum showing bands employed in remote sensing.

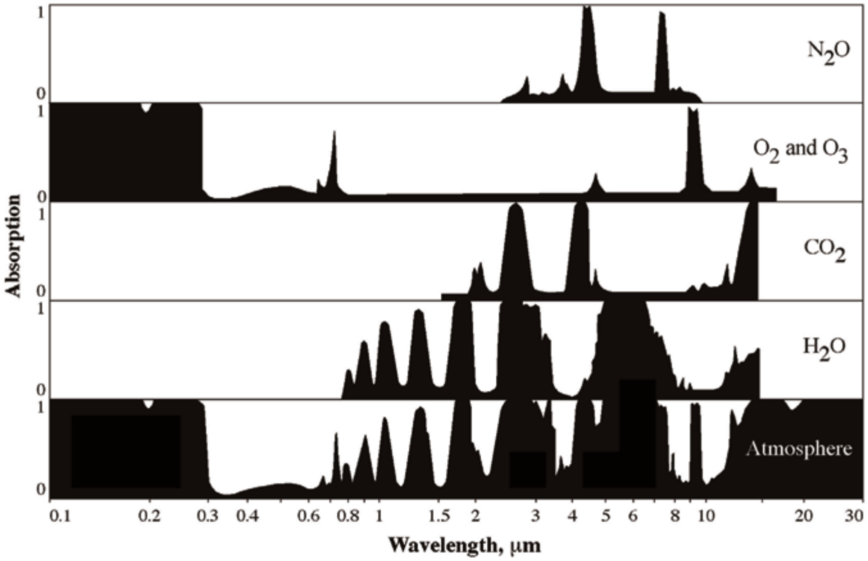


Fig. 6.2: Absorption of the sun's incident electromagnetic energy by various atmospheric gases.

of narrow wavelength bands and record the information electronically. It measures the spectral response of the landscape in two or more wavelength bands of the spectrum. *Thermal sensors* directly measure the emitted thermal energy of the earth's surface. Surface temperature changes are the result of balance of radiant, latent, sensible and ground heat fluxes. *Microwave sensors* directly measure the dielectric properties of the earth's surface. Any changes in these properties directly affect the reflectivity or emissivity measured by microwave systems. A narrow beam of coherent visible or near-IR light is projected which measures the reflected energy with a photomultiplier tube to determine the distance between the laser system and the object of interest in *Laser remote sensing*.

The first aerial photograph (using camera) of the earth from very high altitude (160-320 km) was acquired after World War II in 1964. Gemini mission (1964-65) orbited the earth at an altitude of 640-1360 km. Apollo mission used 35 mm automatic camera and took interesting multi-spectral photographs of Alabama in 1969. *Aerial photography* is limited to optical wavelengths, which are composed of ultraviolet (UV), visible and near IR. It is obtained from air-borne camera using black and white, colour or colour IR films on a scale ranging from 1:5,000 to 120,000. Aerial photographs (mono and stereo coverage) are visually interpreted based on their tone, texture, shape, pattern, proximity etc. in identifying surface objects. Stereo photographs are used widely in terrain classification and measurement of elevations. Black and white or colour panchromatic/Infrared (IR) aerial

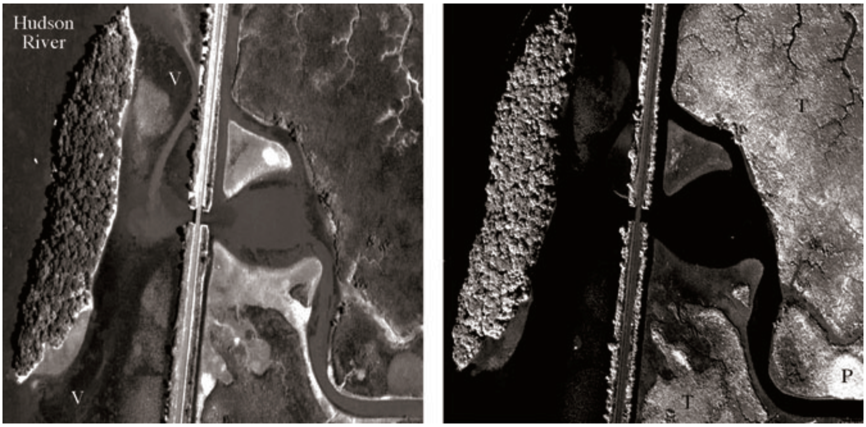


Fig. 6.3: Panchromatic (left) and Black & White (right) infrared aerial photograph – Tivoli North Bay on the Hudson River, NY.

photographs are being effectively used. The use of colour transparencies gives the sharpness of dynamic range for interpretation in natural disaster studies (Fig. 6.3). Aerial photography has the advantage of offering instantaneous scene exposure, resolution and stereoscopic capability, but it cannot be used during rainy season and cloudy days. Governmental flying restrictions and procurement procedures are often restrictive to the progress in addition to flying conditions. The quality of photographs deteriorates with the multiple use and there exists a limitation of enlargement/reduction from the original. The cost of the photography is quite high and weather conditions determine the flight plan and photography operation. Ortho-photographs are different from normal aerial photographs and they exhibit elevation aspects. Data collection from multi-stage platform using multiple-view approach, from the multi-spectral sensors available onboard for the multi-temporal period, would offer accurate information about the event. Spectral sensitivity of the three layers of normal colour and colour IR film is shown in Fig. 6.4.

6.2 Orbital Satellites

Konstantin Tsiolkovsky (1903) in his publication entitled “The Exploration of Cosmic Space by Means of Reaction Devices” described the use of rocketry to launch spacecraft and he has calculated the orbital speed required for a minimal orbit around the earth to be 8 km/s. A multi-stage rocket fuelled by liquid propellants could be used to achieve this. He proposed the use of liquid hydrogen and liquid oxygen in addition to other combinations. He aspired the use of orbiting spacecraft for detailed peaceful and military observations of the ground and described its usefulness for scientific

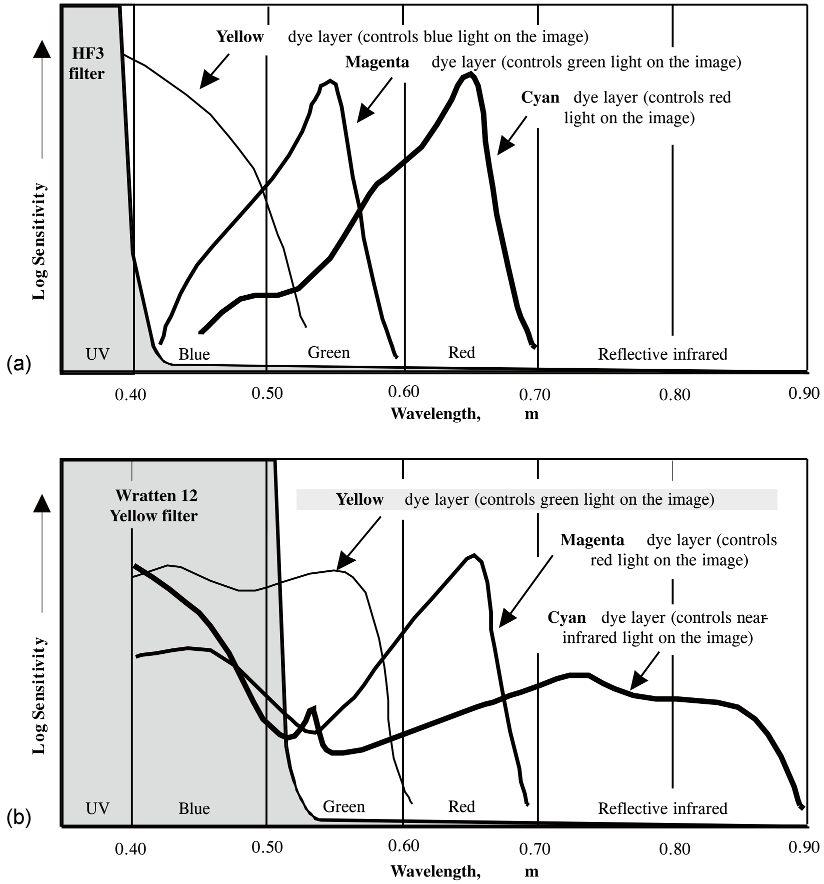


Fig. 6.4: Spectral sensitivity of the three layers of (a) normal and (b) colour infrared films.

experiments. Fiction writer Arthur C. Clarke (1945) described in detail the possible use of communication satellites for mass communications. He also examined the logistics of satellite launch, possible orbits and other aspects of the creation of a network of world-circling satellites, pointing to the benefits of high-speed global communications. He also suggested that three geostationary satellites would provide coverage over the entire planet.

The first artificial satellite was Sputnik 1, launched by the Soviet Union on 4 October 1957 under the Soviet Sputnik programme. Sputnik 1 helped to identify the density of high atmospheric layers through measurement of its orbital change and provided data on radio-signal distribution in the ionosphere. The satellite's body was filled with pressurized nitrogen. Sputnik 1 also provided the first opportunity for meteoroid detection. As a loss of internal pressure due to meteoroid, penetration of the outer surface would have been evident in the temperature data sent back to earth. Sputnik 2 was launched on November 3, 1957 and carried the first living passenger – a dog named Laika, into orbit. Explorer 1 became the United States' first satellite on January 31, 1958. United States Space Surveillance Network (SSN) has been tracking space objects since 1957. It has tracked more than 26,000 space objects orbiting earth and tracking more than 8000 man-made orbiting objects. Other space objects have re-entered earth's turbulent atmosphere and disintegrated, or survived re-entry and impacted the earth. At present there are 560 satellites and the rest are space debris.

Non-military satellite services are the fixed satellite services that handle hundreds of billions of voice, data, and video transmission tasks across all countries and continents. *Mobile satellite* systems help connect remote regions, vehicles, ships and aircraft to other parts of the world and/or other mobile or stationary communication units, in addition to serving as navigation systems. *Scientific research satellite (commercial and noncommercial)* provide us with meteorological information, land survey data (e.g., remote sensing), and other different scientific research applications such as earth science, marine science, and atmospheric research. *Astronomical satellites* are used for observation of distant planets, galaxies, and other outer space objects. *Biosatellites* are satellites designed to carry living organisms, generally for scientific experimentation. *Communications satellites* are stationed in space for the purpose of telecommunications. Modern communication satellites typically use geosynchronous orbits: Molniya orbits or Low Earth orbits.

Navigational satellites use radio time signals transmitted to enable mobile receivers on the ground to determine their exact locations. The relatively clear line of sight between the satellites and receivers on the ground, combined with ever-improving electronics, allows satellite navigation systems to measure location to accuracies in the order of a few metres in real time. *Reconnaissance satellites* are earth observation or communication satellites deployed for military or intelligence applications. Little is known about the full power of these satellites, as governments who operate them usually keep information pertaining to their reconnaissance satellites classified. *Tether satellites* are satellites which are connected to another satellite by a thin cable called a tether. *Weather satellites* are primarily used to monitor Earth's surface and climate. *Earth observation satellites* are satellites intended for non-military uses such as environmental monitoring, meteorology, map making etc. Space stations are man-made structures that are designed for human beings to live on in outer space. A space station is distinguished from other manned spacecraft by its lack of major propulsion or landing facilities — instead, other vehicles are used as transport to and from the station. Space stations are designed for medium-term living in orbit, for periods of weeks, months, or even years. *Miniaturized satellites* are satellites of unusually low weights and small sizes. New classifications are used to categorize these satellites: *Minisatellite* (500–200 kg), *Microsatellite* (below 200 kg), *Nanosatellite* (below 10 kg).

6.3 Satellite Orbit

Sputnik 1 was put into orbit around earth and was therefore in *geocentric orbit*. By far this is the most common type of orbit with approximately 2456 artificial satellites orbiting the earth. Geocentric orbits may be further classified by their altitude, inclination and *eccentricity*. The commonly used altitude classifications are *Low Earth Orbit (*LEO – below 2000 km), *Medium Earth Orbit* (MEO – > 2000 km and < 35786 km) and *High Earth Orbit* (HEO – > 35786 km). **Inclination classifications:** *Inclined orbit* – An orbit whose inclination in reference to the equatorial plane is not zero degrees. *Polar orbit* – An orbit that passes above or nearly above both poles of the planet on each revolution. Therefore it has an inclination of (or very close to) 90 degrees. *Polar sun synchronous orbit*: A nearly polar orbit that passes the equator at the same local time on every pass that helps in imaging process to have the same shadows on every pass (Fig. 6.5). **Centric classifications:** *Galactocentric orbit:* An orbit about the centre of a galaxy and earth's sun follows this type of orbit about the galactic centre of the Milky Way. *Heliocentric orbit:* An orbit around the Sun. Moons by contrast are not in a heliocentric orbit but rather orbit their parent planet. *Geocentric orbit*: An orbit around the planet earth, such as the Moon or artificial satellites. Currently there are approximately 2465 artificial satellites orbiting the earth. *Areocentric orbit:* An orbit around the planet Mars, such as moons or artificial satellites.

Eccentricity classifications: *Circular orbit:* An orbit that has an eccentricity of 0 and whose path traces a circle. *Hohmann transfer orbit:* An

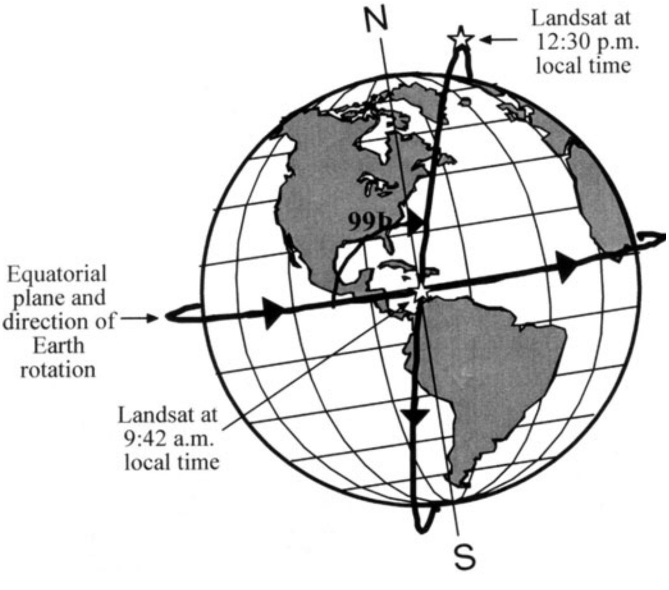


Fig. 6.5: Landsat orbital path and direction of each rotation.

orbital maneuver that moves a spacecraft from one circular orbit to another using two engine impulses. This maneuver was named after Walter Hohmann. *Elliptic orbit:* An orbit with an eccentricity greater than 0 and less than 1 whose orbit traces the path of an ellipse. *Geosynchronous transfer orbit*: An elliptic orbit where the perigee is at the altitude of a Low Earth Orbit (LEO) and the apogee at the altitude of a geosynchronous orbit. *Geostationary transfer orbit:* An elliptic orbit where the perigee is at the altitude of a Low Earth Orbit (LEO) and the apogee at the altitude of a geostationary orbit. *Molniya orbit:* A highly elliptic orbit with inclination of 63.4° and orbital period of half of a sidereal day (roughly 12 hours). Such a satellite spends most of its time over a designated area of the planet. *Tundra orbit:* A highly elliptic orbit with inclination of 63.4° and orbital period of one sidereal day (roughly 24 hours). Such a satellite spends most of its time over a designated area of the planet. *Hyperbolic orbit:* An orbit with the eccentricity greater than 1. Such an orbit also has a velocity in excess of the escape velocity and as such, will escape the gravitational pull of the planet and continue to travel infinitely. *Parabolic orbit:* An orbit with the eccentricity equal to 1. Such an orbit also has a velocity equal to the escape velocity and therefore will escape the gravitational pull of the planet and travel until its velocity relative to the planet is 0. If the speed of such an orbit is increased it will become a hyperbolic orbit. *Escape orbit (EO):* A high-speed parabolic orbit where the object has escape velocity and is moving away from the planet. *Capture orbit:* A high-speed parabolic orbit where the object has escape velocity and is moving towards the planet.

Synchronous orbital classifications: *Synchronous orbit:* An orbit where the satellite has an orbital period equal to the average rotational period (earth's is: 23 hours, 56 minutes, 4.091 seconds) of the body being orbited and in the same direction of rotation as that body. To a ground observer such a satellite would trace an analemma in the sky. *Semi-synchronous orbit (SSO):* An orbit with an altitude of approximately 20,200 km (12,544.2 miles) and an orbital period of approximately 12 hours. *Geosynchronous orbit (GEO):* Orbits with an altitude of approximately 35,786 km (22,240 miles). Such a satellite would trace an analemma in the sky. *Geostationary orbit (GSO):* A geosynchronous orbit with an inclination of zero. To an observer on the ground this satellite would appear as a fixed point in the sky. *Clarke orbit*: Another name for a geostationary orbit. *Supersynchronous orbit:* A disposal/storage orbit above GSO/GEO. Satellites will drift west. Also a synonym for Disposal orbit. *Subsynchronous orbit*: A drift orbit close to but below GSO/GEO. Satellites will drift east.

Graveyard orbit: An orbit a few hundred kilometres above geosynchronous where satellites are moved into at the end of their operation. *Disposal orbit:* A synonym for graveyard orbit. *Junk orbit:* A synonym for graveyard orbit. *Areosynchronous orbit:* A synchronous orbit around the planet Mars with an orbital period equal in length to Mars' sidereal day. *Areostationary orbit (ASO):* A circular areosynchronous orbit on the equatorial plane and about 17,000 km (10,557 miles) above the surface. To an observer on the ground this satellite would appear as a fixed point in the sky. *Heliosynchronous orbit:* A heliocentric orbit about the Sun where the satellite's orbital period matches the Sun's period of rotation. These orbits occur at a radius of 24,360 Gm around the Sun, a little less than half of the orbital radius of Mercury. *Sun-synchronous orbit:* An orbit which combines altitude and inclination in such a way that the satellite passes over any given point of the planets' surface at the same local solar time. Such an orbit can place a satellite in constant sunlight and is useful for imaging, spy, and weather satellites. *Moon orbit:* The orbital characteristics of earth's moon and its average altitude of 3,84,403 km (2,38,857 miles), elliptical-inclined orbit. The orbital calendar of satellite path and row are determined prior to launching to have desired overlap of scene coverages. Successive satellite orbits over the earth's surface are illustrated in Fig. 6.6.

Pseudo-orbit classifications – *Horseshoe orbit:* An orbit that appears to a ground observer to be orbiting a certain planet but is actually in co-orbit with the planet. *Exo-orbit*: A maneuver where a spacecraft approaches the height of orbit but lacks the velocity to sustain it. *Suborbital spaceflight* is synonym for exo-orbit. *Lunar transfer orbit* (LTO) *Prograde orbit:* An orbit with an inclination of less than 90°; or rather, an orbit that is in the same direction as the rotation of the primary. *Retrograde orbit:* An orbit with an inclination of more than 90°; or rather, an orbit counter to the direction of rotation of the planet. Apart from those in sun-synchronous orbit, few satellites are launched into retrograde orbit because the quantity of fuel required to launch them is much greater than for a prograde orbit. This is because when the rocket starts out on the ground, it already has an eastward component of

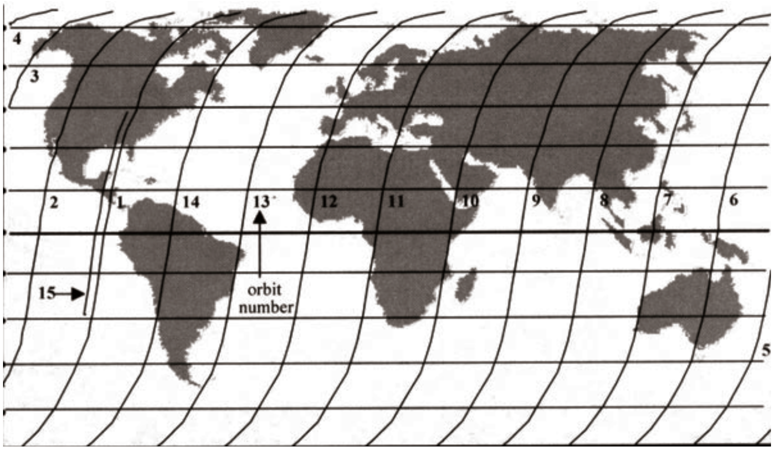


Fig. 6.6: Successive orbital paths of Landsat.

velocity equal to the rotational velocity of the planet at its launch latitude. *Halo orbit* and *Lissajous orbit:* Orbits 'around' Lagrangian points.

Russia and Ukraine (and not USSR), USA, Japan, China, India, and Israel and European Space Agency (ESA – UK and France) have independently launched satellites on their own indigenously developed launch vehicles. Several other countries, including South Korea, Iran, Brazil, Pakistan, Romania, Kazakhstan, Australia, Malaysia and Turkey, are at various stages of development of their own small-scale launcher capabilities, and seek membership in the club of space powers. Iran already has successfully tested its own space launch vehicle (Kavoshgar 1) and is scheduled to put its first domestic satellite (Omid 1) into orbit within a year. *Security of satellite:* In recent times satellites have been hacked by militant organizations to broadcast propaganda and to pilfer classified information from military communication networks. Satellites in low earth orbit have been destroyed by ballistic missiles launched from earth. Both Russia and the United States have demonstrated ability to eliminate satellites. In 2007 the Chinese military shot down an aging weather satellite, followed by the US Navy shooting down a defunct spy satellite in February 2008. Russia and the United States have also shot down satellites during the Cold War. Due to the low received signal strength of satellite transmissions they are prone to *radio jamming* by land-based transmitters. Such jamming is limited to the geographical area within the transmitter's range. GPS satellites are potential targets for jamming, but satellite phone and television signals have also been subjected to jamming.

6.4 Commercial Satellite

There are numerous communication, weather and earth observation satellites available for earth surface observation monitoring and assessment. Table 6.1 shows the meteorological and communication satellites that are used for drought observation purposes. Even some of the defense satellites are also used in emergency situation. The information from the control room to specific groups/agencies involved in the disaster mitigation is transmitted through *Communication satellites*. Commercial sectors also play an important role in global communication systems such as INTELSAT and INMARSAT programs. Additional low earth orbit satellites are planned by IRIDIUM (Motorola), ODYSSY (TRW), Goldstar (Loral/Qualcomm) and Project 21 (INMARSAT) in providing communication network in addition to INSAT (ISRO). Further, stationary and mobile, very small aperture terminals (VSAT) and ultra small aperture terminals (USAT) and array of antennae help in position, location and co-ordination of disaster relief operations, in addition to services. *Weather satellites* such as NOAA and INSAT provide continuous information on atmospheric and surface features. *Earth observation satellites* provide comprehensive synoptic and temporal view of large areas in real time.

Table 6.1: Meteorological and communication satellites

Spectral bands	*Tiros-N*	*NOAA-6,8,10*	*NOAA-7,9,d,H,I,J*
Meteorological satellites			
1	0.55-0.90	0.58-0.68	0.58-0.68
2	0.725-1.00	0.725-1.00	0.725-1.00
3	3.55-3.93	3.55-3.93	3.55-3.93
4	10.50-11.50	10.50-11.50	10.30-11.30
5	Nil	Nil	11.50-12.50
Altitude	833-870 km		
Resolution	Large Area Coverage – 1 km; Global Area Coverage – 4 km		
Image swath width	2253 km		
Repeat coverage	Daily worldwide		
TIROS (USA) 1965	Measurement and picture transmission		
MIBUS 1964-1978	Night time picture, TV coverage and 24 hr weather		
NOAA	Severe storm support, geo-stationary, atmospheric condition		
Geo-stationary	Rainfall Volcanic eruption, Fire detection, Oceanography		
Operational Environment Satellite			

Communication Satellite	*Functions*
Starsys	Global message/position services
Worldstar	
Teledesic -LEO	High speed computer link
Irridum	
INSAT 2E (Launch)	Communication 12- transponders normal C
2A 10-7-1992	5- transponders lower C
2B 23-7-1993	
2C 7-10-1995	
INSAT 1-1990	
3A 2000-2001	

They are being effectively used in detecting and mapping of many types of natural disasters and planning and if the disasters are identified in the initial stages, it is easier to reduce the social and economic impacts. Polar orbital Earth Resources Satellites have optical sensors that cannot see through clouds operating at low (AVHRR), medium (LANDSAT, SPOT, IRS) and high (IKONOS) ground resolution and high resolution microwave sensors (Synthetic Aperture Radar) that can see through clouds (RADARSAT, ERS, JERS) and low resolution passive sensors (SSMI). Table 6.2 lists out the satellite mission, payload sensors and spectral and spatial resolution.

Table 6.2: Satellite missions and their scanners

Satellite mission	*Sensor*	*Spectral bands*	*Resolution*
IRS 1A/1B (22 days)	LISS-1	0.45-0.52 µm	72.5
INDIA		0.52-0.59 µm	
		0.62-0.68 µm	
		0.77-0.86 µm	
IRS 1C (1995)	PAN	0.50-0.75 µm	5.8 70/148 km
IRS 1D (1999)	LISS-III	0.52-0.59 µm	23.5
INDIA		0.62-0.68 µm	
(24/25 days)	WiFS	0.77-0.86 µm	188
		0.62-0.68 µm	
		0.77-0.86 µm	
IRS-P3 (24 days)	MOS-A	7.55-7.68 µm (4 channels)	2500 × 2500
INDIA	MOS-B	4.08-10.10 µm (13 channels)	727 × 580
	MOS-C	15-17 µm	1000 × 727
IRS-P4	OCM	0.402-0.422 µm	360 × 236 m
(Oceansat)		0.433-0.453 µm	
		0.480-0.500 µm	
		0.500-0.520 µm	
		0.545-0.565 µm	
		0.668-0.680 µm	
		0.745-0.785 µm	
		0.845-0.885 µm	
	MSMR	6.6,10.65,18.7,21.3 GHz, V & H	
		0.50-0.75 µm	120, 75, 45, 40 m
IRS-P5	PAN (2)		2.5 m
Cartosat			
IRS-P6	LISS-IV		2
Resourcesat (5 days)	LISS-III		23
	WiFS		80
LANDSAT (16 days)	MSS	0.5-0.6 µm	80
USA		0.6-0.7 µm	
		0.7-0.8 µm	
LANDSAT 4 (1982)		0.8-1.1 µm	
LANDSAT 5 (1984)	TM	0.45-0.52 mm	30
		– Penetration of water, soil/water discrimination	
		0.52-0.60 µm	
		– Vegetation vigour assessment	
		0.63-0.69 µm	
		– Chlorophyll absorption, plant species identification	
		0.76-0.79 µm	
		– Vegetation type, vigour, bio-mass, soil moisture	

(*Contd.*)

Table 6.2 (*Contd.*)

		1.55-1.70 µm – Vegetation and soil moisture, snow from cloud 10.4-12.5 µm – Vegetation stress analysis and thermal anomaly 2.08-2.35 µm – Mineral/rock identification, vegetation moisture	120 m
Clark (1996)			3
Lewis (1996)			5
TRMM (1997)		Radar	2000
Orbview (USA/Saudi)			1 m
EOS-colour			1100 m
EOS-AM1			15, 30, 90
EOS-PM1			250 m
ICONOS	PAN/MLA	1 band in PAN and 3 in visible	1 m
AMI-Aster		2 bands in visible and 7 in IR	15 m and 30 m
SPOT 1/2 (26 days)	PLA	0.51-0.73 µm	10
FRANCE	MLA	0.50-0.59 µm	20
SPOT 1 (1986)		0.61-0.68 µm	
SPOT2 (1990)		0.79-0.89 µm	
SPOT3 (1997)			10 m
SPOT4 (1999)			
ERS-1 (168, 35, 5 days)		Radar	10 m
ESA (1991)			
ERS-2 (1995)			250, 10 m
ENVISAT			
Almaz-1 (1991)		Radar	10 m
RUSSIA			
Almaz-2 (1996)			5
Resours 2 (1995)			20
JERS-1 (1992)		0.52-0.60, 0.63-0.69, 0.76-0.80, 1.60-1.71, 2.13-2.25, 2.01-2.40 µm	20 m
JAPAN			
ADEOS-1 (1996)			8 m
ADEOS-2 (1999)			8 m
Radarsat (1995)		Radar	10 m
CANADA			
CBERS (1995) (China/Brazil)		3 in visible and 4 in IR bands	20 and 80 m

Readers are requested to check up with the data product suppliers about the availability of good quality data.

Meteorological satellites are geo-stationary and polar orbital in nature (ref chapter meteorology). Geo-stationary satellite (GOES) observes the weather on a continuous basis from an altitude of 22,000 miles and transmits the picture at a frequency of 15 minutes (GOES8 & 10). METEOSAT from European Space Agency, GMS of Japan's Geo-stationary Meteorological Satellite, INSAT of Indian national satellite and Russian satellite GOMS also offer weather information on visible (VIS) and infrared (IR) wavelengths. Polar orbital satellites orbit the earth twice a day at an altitude of 850 km. Special sensor Microwave Imager (SSM/I) onboard of Defense Meteorological Satellite Program satellite and Advanced Microwave Sensing Unit in NOAA15 generate data on microwave in addition to VIS and IR wavelength. The information from the NOAA, METEOSAT, INSAT and GMS, NOAA/AVHRR and IRS/WiFS, SPOT4, DMSP/SSMI and IRS-P4/MSMR, TRMM, RESOURCESAT, MODIS and MERIS and LANDSAT, IRS and SPOT satellites are being used for prediction, vegetation cover monitoring/early warning, drought information, monitoring and drought management purposes.

6.5 Sensors and Products

Passive remote sensing systems record the electromagnetic energy that is reflected (e.g., blue, green, red, and near-infrared light) or emitted (e.g., thermal infrared energy) from the surface of the earth. There are also active remote sensing systems that are not dependent on the sun's electromagnetic energy or the thermal properties of the earth. Active remote sensors create their own electromagnetic energy that (1) is transmitted from the sensor toward the terrain (and is largely unaffected by the atmosphere), (2) interacts with the terrain producing a backscatter of energy, and (3) is recorded by the remote sensor's receiver. Scanner, radiometer and camera, positioned on the ground, truck mounted, low/altitude air-borne and space-borne platforms are used in data collection. Air- and space-borne on-board sensors that are in various satellites and their spectral and ground resolution details are listed in Table 6.3. The spectral characteristics measured by hand-held radiometer and truck and aircraft mounted sensors were used in the spectral signature collection. This information was used in designing the sensors and also in differentiation of diverse surface cover factors. Spectral characteristics of the land cover object as recorded by different bandwidths and Landsat TM bands that are suitable for identification of vegetation are shown in Fig. 6.7. These curves are used in selection of suitable bandwidth for spectral classification land cover vegetation/stunted crop etc. Hand-held passive spectral radiometer with MSS bandwidths came into operation for ground level object differentiation, followed by truck-mounted instruments, air-borne and orbital satellite sensors. AVIRIS imaging spectrometer operates in the

Table 6.3: Radar wavelength and frequencies used in aircraft radar system

Band	*Wavelength (cm)*	*Frequency GHz (10^9 cycles/sec^{-1})*	
Ka (0.86 cm)	0.8-1.1	40.0-26.5	
K	1.1-1.7	26.5-18.0	
Ku	1.7-2.4	18.0-12.5	
X (3.0 and 3.2 cm)	2.4-3.8	12.5-8.0	
C	3.8-7.5	8.0-4.0	
S	7.5-15.0	4.0-2.0	
L (23.5 and 25 cm)	15.0-30.0	2.0-1.0	
P	30.0-100.0	1.0-0.3	
Characteristics	*Seasat (1978)*	*SIR-A (1981)*	*SIR-B (1984)*
Repeat coverage	Irregular, northern hemisphere	Little to none	Little to none
Resolution	25 × 25 m	40 × 40 m	25 × (17-58) m
Wavelength (23.5 cm)	L band	L band	L-band
Altitude	790 km	250 km	225 km
Image swath width	100 km	50 km	40 km
Thermal scanners			
Shuttle Multi-spectral Infrared Radiometer			5 channels within 2.0-2.4 μm 5 channels within 0.4-1.8 μm
Heat Capacity Mapping Mission			10.5-12.5 μm
Very High Resolution Radiometer			3.55-3.93 μm

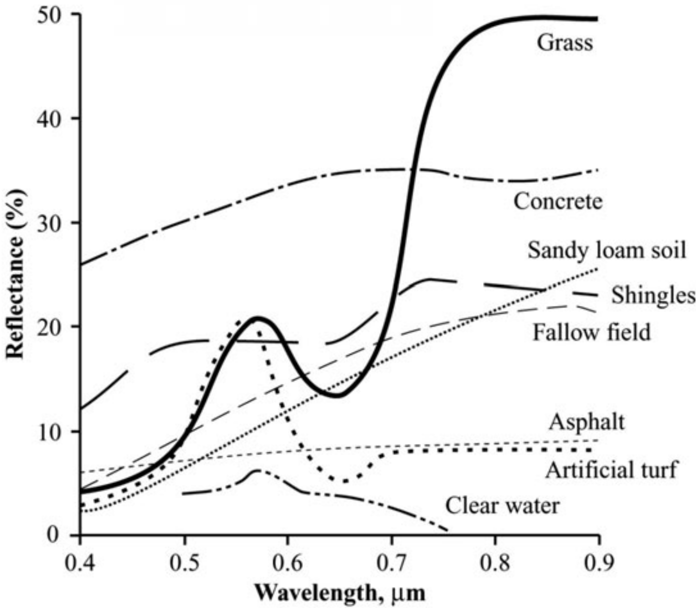


Fig. 6.7: Spectral reflectance curves of selected materials.

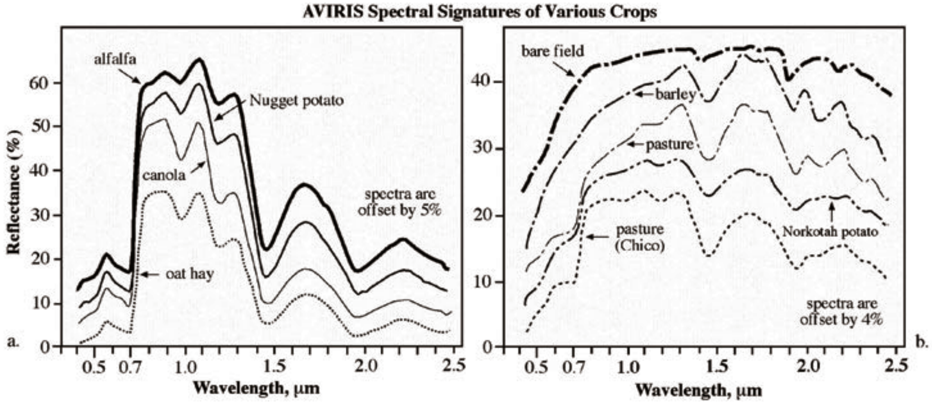


Fig. 6.8: Spectral characteristics of healthy vegetation using AVIRIS - 224 channels each 10 nm wide with 20 × 20 m pixels.

wavelength band of 0.4 to 2.5 µm and has 224 channels with a spectral bandwidth of 10 nm and pixel resolution of 20 × 20 m. The finer spectral resolution bandwidth sensors of this nature are used in differentiating crop status (Fig. 6.8). Detector configuration used in panchromatic, multispectral and hyper-spectral remote sensing is shown in Fig. 6.9.

Radar is an active sensor that produces its own illumination. Radar pulse illuminates the terrain and receives and arranges these reflective signals into images that can be evaluated. These images appear similar to that of black and white photographs. Geological and geomorphologic features could be interpreted based on tone, texture, shape and pattern. It is acquired in X, K and Ka band wavelengths. X-band air-borne radar systems are the most commonly offered by commercial contractors. Real Aperture Radar (RAR) uses an antenna of the maximum practical length to produce a narrow angular beam width equal to azimuth/flight line direction. Synthetic Aperture Radar (SAR) achieves higher resolution without physically large antenna through complex electronic processing of the acquired signal. Table 6.3 shows the various band designations of SAR data and its application. Areas can be surveyed with radar much more rapidly to produce an excellent synoptic view even during cloudy and rainy weather conditions. Distance can be measured more accurately. The long wavelength of the radar system permits potential sub-surface penetration between 2 and 3 m over extremely dry sand. SIR series of radar data is expected to continue with SIR-C and so on. Radarsat (Canada), a C-band (6.0 cm) system, is designed to provide worldwide stereoscopic coverage. European Space Agency has launched C-band SAR in its Earth Resource Satellite (ERS) and Japan launched L-band radar programme.

Thermal infrared scanners imagery shows the surface thermal conditions of the terrain. *Thermal infrared energy* is emitted from all objects that have

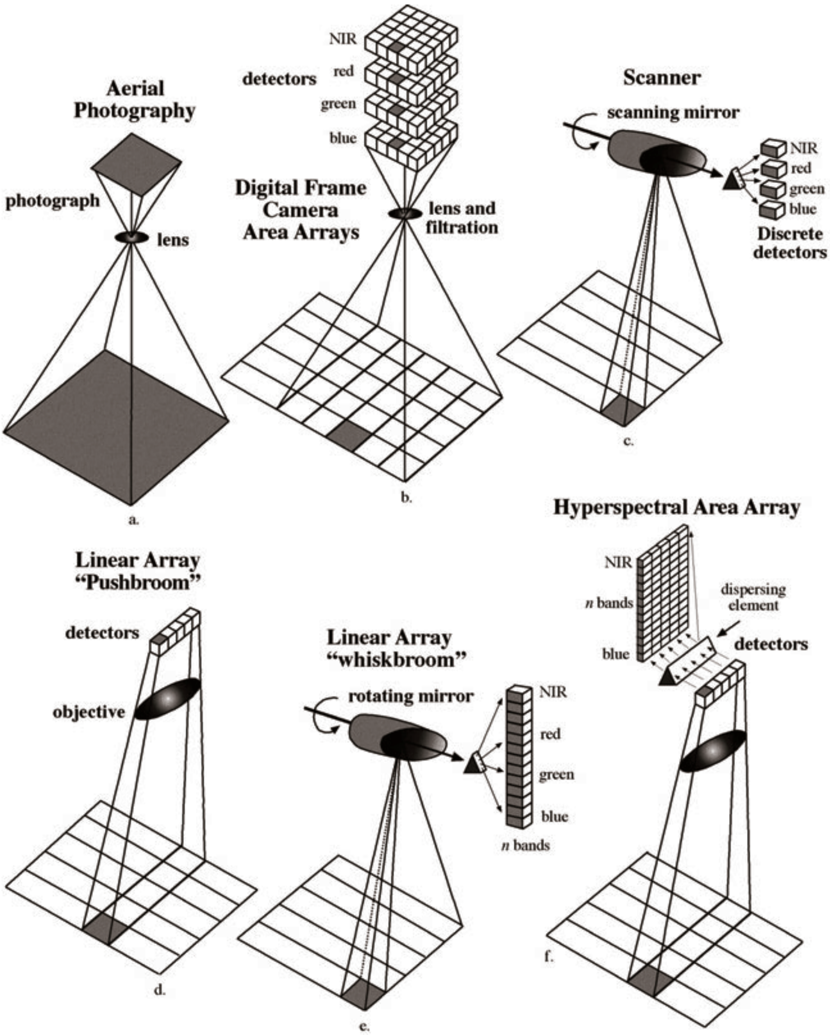


Fig. 6.9: Detector configurations used for panchromatic, multispectral and hyperspectral remote sensing.

a temperature greater than absolute zero. Therefore, all the features we encounter in the landscape on a typical day (Sun, vegetation, soil, rocks, water, and even people) emit thermal infrared electromagnetic radiation. Humans sense thermal energy primarily through the sense of touch. Our eyes cannot detect differences in thermal infrared energy. Fortunately, engineers have developed detectors that are sensitive to thermal infrared radiation. These thermal infrared sensors allow humans to sense a previously invisible world of information as they monitor the thermal characteristics of the landscape. Thermal infrared detectors are usually composed of: In:Sb (indium antimonide) with a peak sensitivity near 5 μm; Gd:Hg (mercury-doped germanium) with a peak sensitivity near 10 μm, or Hg:Cd:Te (mercury-cadmium-telluride) sensitive over the range from 8 to 14 μm. The detectors are cooled to low temperatures (–196 °C; –243 °C; 73 °K) using liquid helium or liquid nitrogen. Cooling the detectors ensures that the radiant energy (photons) recorded by the detectors comes from the terrain and not from the ambient temperature of objects within the scanner itself.

ASTER – *Advanced Space borne Thermal Emission and Reflection Radiometer* has spectral range in VNIR 0.4-14.4 mm (in three bands), SWIR 1.6-2.5 mm (in six bands), and TIR 8-12 mm (in five bands). They have spatial resolution of 15 m, 30 m and 90 m for VNIR, SWIR and TIR bands respectively. Spatial resolution of scanner decreases with altitude above the terrain and is effectively used in lower altitudes (below 3000 μm). 3.0 to 5.5 μm band provides the best information for active volcanic vent, thermal spring's etc., while 8.0 to 14.0 μm band provides the ambient cooler temperatures such as flooding streams under canopies, warm springs etc.

Thermal images depict the temperature conditions around volcanic crater. These images (night time) are useful in demarcating the cold/hot water springs in an arid/semi-arid region. It is best suited for known areas or suspected areas of volcanism, trapping of water in fault, landslide slumps, and moisture conditions associated with karst terrain. *Advanced Very High-Resolution radiometer (AVHRR)* on board the NOAA-7 is useful for natural hazard assessment, because of its low resolution (1.1 km at nadir). It has band-1 (green to red), band-2 (red to reflectance IR), band-3 (middle IR), band-4 (thermal IR) and band-5. The large swath width of 2253 km provides day and night coverage of the earth surface. Vegetation health conditions of the continents are being monitored using this data. Wisnet and Deustch (1986) successfully utilized these data in the delineation of flood areas within 48 hours of the event.

The most widely used active remote sensing systems include: active microwave (RADAR), which is based on the transmission of long-wavelength microwaves (e.g., 3-25 cm) through the atmosphere and then recording the amount of energy back-scattered from the terrain; LIDAR, which is based on the transmission of relatively short-wavelength laser light (e.g., 0.90 mm) and then recording the amount of light back-scattered from the terrain; and SONAR, which is based on the transmission of sound waves through a water column and then recording the amount of energy back-scattered from the bottom or from objects within the water column. *Light Detection And Ranging (LIDAR)* is an air-borne system, which uses its laser light to illuminate the terrain. It is operated either in a profiling (bathymetry) or scanning mode. It is used for measuring timber heights and estimates the standing bio-mass. Its Laser-Induced Fluorescence (LIF) induces the fluorescent of the earth surface. It is used for oil slicks, water pollutants and chlorophyll concentration in natural water bodies. *Moderate Resolution Imaging Spectro-radiometer (MODIS)* with 36 channels spread over the wavelength of 0.415-14.235 μm with spatial resolution of 250 m and 1 km of 16 days would provide together a range of biophysical variables and details such as land cover changes and its extent for drought monitoring. Some of the sensors/cameras were tested on board aircraft and satellite platforms, in addition to truck-mounted vehicles. Orbital satellite data collection is in operational mode for some of the earth's resources-based applications.

Since 1972, sun-synchronous Land st series of satellites are in operation (previously known as Earth Resources Technology Satellite – ERTS). The ground (smallest object on the ground) and spectral (EMR) resolution of the sensors used in the satellite/air-borne sensors were improved with advancement of technology. Narrow spectral and spatial resolution of the scanners/sensors mounted on the air and space borne platform can detect ground objects of <1 sq.m area and also continuous global and regional coverage. Field level identification of stunted crops and fallow land is required in the crop loss assessment. One metre resolution IKONOS satellite is useful for this purpose in addition to IRS, SPOT and Landsat data. This has positive effect on the identification of smaller objects and its physical aspects. Data from Landsat5 (USA), SPOT 2/3 (France), IRS1D/P3 (India) in optical and/or thermal spectrum and ERS1/2 (Europe) and Radarsat (Canada) in microwave spectrum are available for usage. There were four spectral bands at 80 m resolution in the Multi Spectral Scanner (MSS). *Thematic Mapper* (TM) has seven spectral bands and six of them are with 30 m resolution in the thermal IR range with 120 m resolution introduced in Landsat4 in 1982. SPOT satellite with its high-resolution visible (HRV) sensors ranges from green wavelength into blue. It has 20 m resolution producing images in stereo-pairs and panchromatic sensor provide 10 m resolution images. Indian remote sensing satellite series has *Linear Image Scanning System* (LISS) with four bands and was introduced in 1990.

Although none of the existing satellites and their sensors have been designed for the observation of natural disaster (presence of satellite over the event location is mostly accidental), the spectral bands in visible and near-IR, in addition to thermal IR range could be effectively integrated and used. They provide enormous data as spectral information about the object viewed under different ground resolution. It could be fused together to interpret and assess the disaster of interest based on the visual interpretation or digital image enhancement and classification techniques. The synergistic use of the data from more than one part of the spectrum would enhance the capability of recognition of an event.

6.6 Spectral Data Analysis

The information collected by satellite and air-borne sensors are available in the photographic format of different scales and also in digital format for analysis. Black and white single band data and colour composite (combination of bands with blue, green, red filters) generated from multiple bands that are geometrically corrected and geo-coded are available for visual interpretation. These products are visually interpreted for thematic information. Digital data is available in the form of computer floppy diskettes, tapes and computer disk etc. for the digital image processing and classification of data.

6.7 Visual Interpretation

The aerial/satellite image is a pictorial presentation of the land surface pattern. Assumed to be composed of element-indicators of things and events, it reflects the physical, biological and cultural components of the landscape. Similar conditions in similar environments reflect similar patterns while unlike conditions reflect unlike patterns. The type and amount of information that can be obtained is proportionate to the knowledge, experience, skill and interest of the analyst, methods used and the awareness of the limitations. Hence there is a need for understanding of the image-forming processes, image-pattern elements, earth features and phenomenon. The skill of extracting information from remotely sensed images is developed through experiences – you learn by doing. The perception and the interpretation of imagery depends on: sensitivity characteristics of the film combination or other detectors, exposure and processing, season of the year, time of the day, atmospheric effects, image scale, resolution characteristics of the imaging system, image motion, stereoscopic parallax, visual and mental acuity of the interpreter, interpretation equipment and technique and training aids. The fundamental image elements used in the visual interpretation are shown in Fig. 6.10. The interpretation is best defined as the process of detecting,

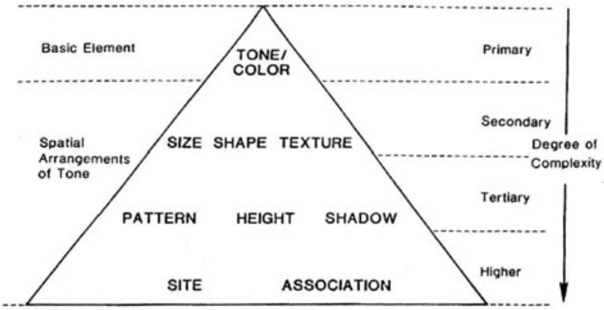


Fig. 6.10: Fundamental elements of image interpretation.

delineating and identifying conditions on images and judging the significance of those features and/or conditions. Image elements that are used in the interpretation are described here.

Tone or colour is the fundamental element of interpretation and represents the relative blackness or whiteness as a result of the amount of light reflected by an object. It varies with object and angle of sun. Theme specialists use this element for interpreting their objects. Colour – a feature has a colour when it reflects particular wavelengths of light. The human eye can distinguish about 1000 times as many hues of colour as it can be tones of grey. False colour infrared film developed during World War II has been found useful for special studies of plant conditions, vegetation distribution, and soil moisture conditions and drainage delineation. *Texture* is created by the frequency of tonal or colour change in groups of objects, which are too small to be discerned as individuals. The size of the object required to produce texture varies with the scale of photography/imaging. The vegetation crown contributes to the texture of the whole stand of trees. Within a given range of scales, the texture of group of objects may be distinctive enough to serve as a reliable clue to the identity of the object.

Pattern is a spatial arrangement of objects. Some patterns are cultural and others are primarily natural. Trained analyst appreciates the significance of remote-sensor imagery mainly through his understanding of patterns on the earth's surface. *Shape* is plan or top view of an object that is so different from the familiar profile or oblique view. It is often proved to be a conclusive indication of the structure, composition and function of the object. In stereoscopic pairs, the observer sees objects in three dimensions and distinguishes close from distant objects. *Shadow* is a familiar phenomena and in ordinary life we often judge the size and shape of objects or persons by observing the shadows they cast. It is helpful if the objects are very small or lack tonal contrast with their surroundings. It is important when inferring depth from planimetric space imagery. *Time* is important when the temporal aspects of the earth phenomena are observed. Considerable additional information is required for interpretation.

Vegetation cover appears bright red to dark on FCC, because of their green foliage, dense canopy cover of the species and greenness. They are smooth in texture and contiguous in spread but occasionally non-contiguous due to tree felling. Depending on the crown density and phonological condition, they were grouped into dense, moderate and low/sparse growth. Vegetation crown density of 40% and above is termed as *dense*; 10-40% as *moderate* and less than 10% as *low/sparse*. Total contrast of agriculture land varies from bright red to red and signifies the greenness of the foliage at different crop growth, phenological conditions (healthy/infected) besides the nature of the soil (moist/dry) and terrain. Size and shape varies with land holdings. It has smooth texture (*mature stage*) to coarse or mottled (early growth stage of plantation). It is contiguous of croplands punctuated by harvested fields of fallow land. *Fallow land* appears white in colour due to the absence of any vegetation cover.

Open area appears distinctly on the imagery in light yellow to light brown colour, smaller in size with regular to irregular shape, coarse to mottled texture, dispersed and scattered amidst forest of all types and sub-types. *Rock out-crop* appears greenish to yellow to brownish in colour with varied size, irregular and discontinuous shape, coarse to medium texture, linear to contiguous and dispersed pattern. Prior to the monsoon, loose leaves, twigs, branches, and roots in the sugarcane fields were burnt which leaves black patches on the surface. This has been demarcated from the image and classified as *burnt-out area.*

Their black to light blue colour, due to its deepness/shallowness identifies *hydrological features*. Vegetation floating on the water surface appears as red patch. *Canals* show their linear pattern, while *river/stream* appears dark blue tone, narrow to wide in size with irregular, sinuous shape, smooth to medium in texture, continuous and nonlinear to dendritic pattern. Silt/sediment laden areas appear bright yellowish white to bluish white in colour depending on the moisture content and found close to water spread. Lake/reservoir appears black in colour with man-made impounding shape. Surface natural vegetation cover density, growth status and area of different crops, water spread of reservoir/lakes, drainage, human settlements, industrial area and infra-structure information during critical stage is essential in drought management. In addition to the above, the groundwater augmentation studies require the favourable fractures (lineament) that could be used in groundwater potential mapping/prospecting. Examples of various interpretative elements described can be observed in the IRS images shown in Fig. 6.11.

Fig. 6.11: IRS false colour composite showing hydrological and land cover features.

6.8 Digital Image Processing

The visual interpretation takes into account the image characteristics and its surroundings while the digital image analyses rely on the digital number (DN) that ranges between 0 and 255 (Fig. 6.12). It involves the manipulation and interpretation of digital images with the aid of computing systems. Input data sources are from satellites (commercial earth resources satellite and meteorological satellites), air-borne scanner data, solid-state camera data, images generated by scanning micro-densitometer and high resolution video cameras. The digital image is fed into a computer one pixel at a time and is programed to insert these data into an equation or series of equation and then store the results of individual pixels. The resultant pixel is displayed or recorded in a pictorial format for interpretation. The operation of the sensors along the path and the Instantaneous Focus of View (IFOV) is dependent on the sensor optics. The dynamic conditions of the atmosphere leading to change in the orbital height and the fluctuation of on-board power supply affect the recording efficiency sensors. The quality and the scene geometry get disturbed by the said operational problems. There is a need to pre-process the image for known and unknown errors.

Pre-processing

Image rectification and restoration operations (pre-processing) are carried out to correct the distorted or degraded image data to create a more faithful representation of the original scene. Raw image data from the sensor is corrected for geometric distortion, to calibrate the data radio-metrically and to eliminate noise present in the data. These errors are due to platform effects (altitude i.e. roll, pitch, yaw variations, scan skew and spacecraft velocity changes), sensor effects (mirror scan non-linearity, detector sampling

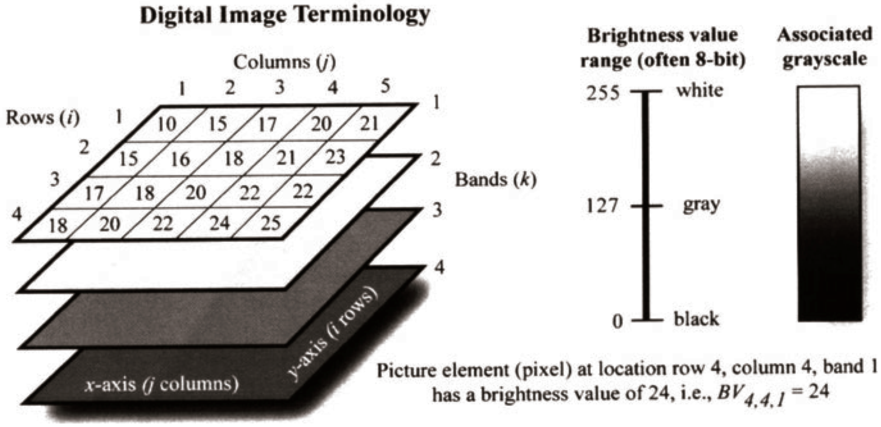


Fig. 6.12: Digital image technology and pixel elements.

delay, detector bias/gain, geometrical perspective and panoramic distortion), scene effects (earth rotation, curvature and elevation) and atmospheric effects (attenuation and scattering). This process is also known as pre-processing operations.

Geometric distortions of the raw digital images are due to variations in altitude, attitude and velocity of the sensor platform to factors such as panoramic distortion, earth curvature, atmospheric refraction, relief displacement and non-linearities in the sweep of a sensor's IFOV along the satellite path. They are grouped into systematic (predictable) and non-systematic (un-predictable) distortions. The intent of geometric correction is to compensate for the distortion introduced by these factors so that the corrected image will have the geometric integrity of a map. *Systematic distortions* are corrected by applying formulas derived by modelling the sources of the distortions mathematically. *Non-systematic distortions* are due to spacecraft movement (Fig. 6.13). A highly systematic source of distortion

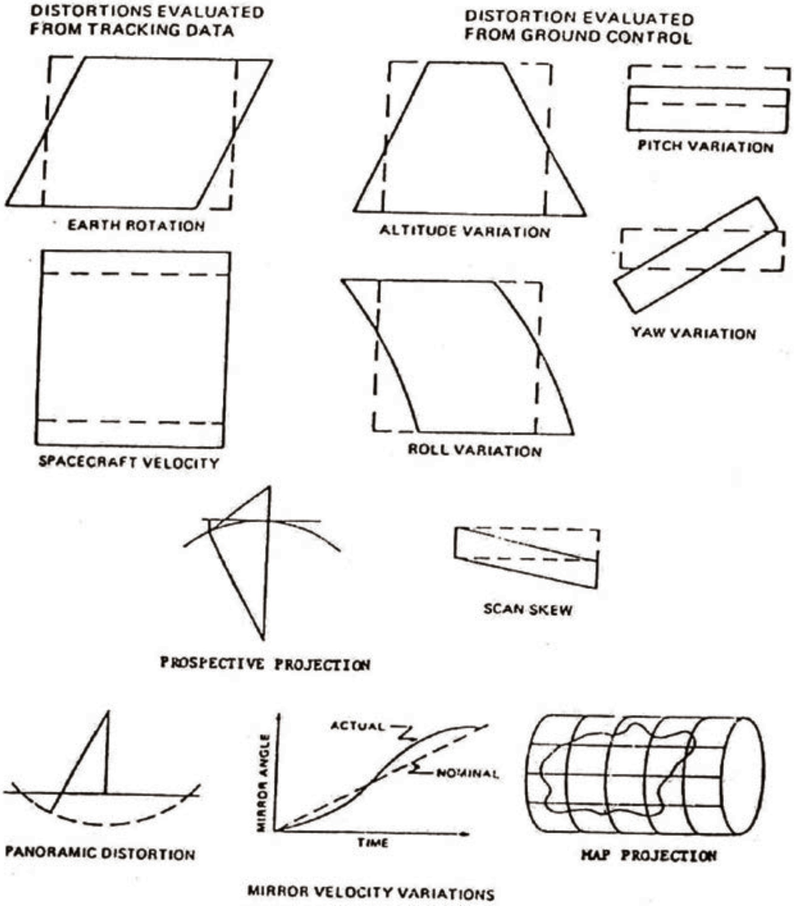


Fig. 6.13: Geometric distortions in orbital satellite images and correction.

involved in multi-spectral scanning from satellite altitudes is the eastward rotation of the earth beneath the satellite during imaging that cause eastward optical sweep to cover an area slightly to the west of the previous sweep. It is known as skew distortion. After the process of de-skewing, the resulting imagery involves offsetting each successive scene line slightly to the west.

Random distortion and residual unknown distortions are corrected by analyzing the well-distributed ground control points (GCP) occurring in an image. GCPs are features of known ground locations that can be identified on the imagery. Good control points are highway intersections and distinct shoreline features. Numerous GCPs are located in terms of their image co-ordinates (column, row numbers) on distorted image and in terms of their ground coordinates (measured from map in terms of UTM coordinates or longitude or latitude). Two co-ordinate transformation equations can be used to inter-relate the geometrically correct (map) co-ordinates and the distorted image coordinates (Fig. 6.14). There are number of re-sampling schemes such as nearest neighbourhood, cubic convolution method, bilinear interpolation techniques etc. available for this purpose.

Radiometric corrections are applied for sensor-related shortcomings due to scene illumination, atmospheric conditions, viewing geometry and instrument response for air-borne data collections only rather than satellite

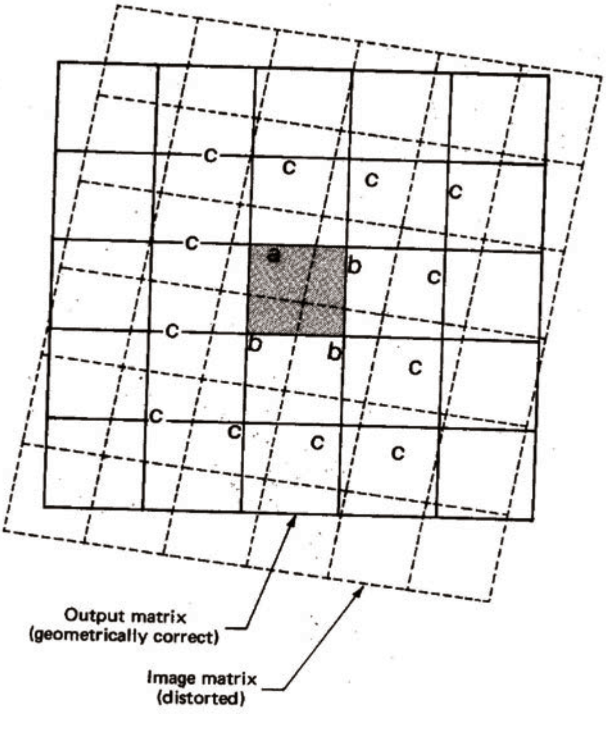


Fig. 6.14: Skew effect and correction.

image acquisition systems. Sun elevation correction accounts for the seasonal position of the sun relative to the earth. Image data acquired under different solar illumination angles are normalized by calculating pixel brightness values assuming that the sun was at the zenith on each date of sensing. This correction ignores topographic and atmospheric effects. Noise removal is done from the images derived from signal digitization or data recording process. The potential sources of noise range from periodic drift or malfunction of a detector, to electronic interference between sensor components, to intermittent "hiccups" in the data transmission and recording sequence. Noise removal usually precedes any subsequent enhancement or classification of the image data. Multi-spectral scanners that sweep multiple scan lines simultaneously often produce data containing systematic striping or banding due to response of individual sensors. Several de-stripping procedures (Fig. 6.15) such as line drop, etc. are used.

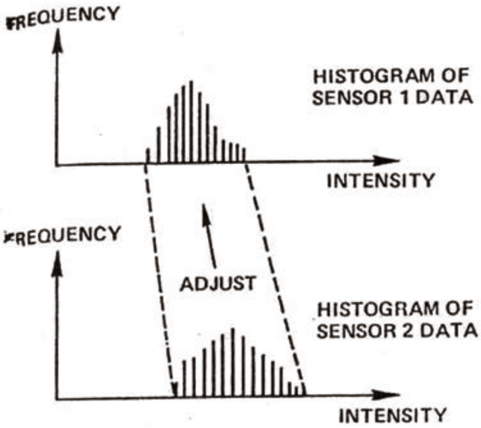


Fig. 6.15: Global de-striping method.

6.9 Image Enhancement

It improves the visual interpretability of an image by increasing the apparent distinction between the features in the scene. These techniques are either point or local operative in nature. Point operators modify the brightness values of each pixel in an image data set independently. Local operations modify the value of each pixel based on neighbouring brightness value. The enhancements can be performed on single band (monochrome) images or on the individual components of multi-image composite. Selection of appropriate enhancement for any particular application is an art and often a matter of personal preference. The satellite data receiving stations carry out radiometric corrections of the raw data. Correction is carried out for deviation of line of sight (MSS optics) from nadir owing to pitch, yaw and roll of the spacecraft, standardization of scan line lengths is done usually by inserting synthetic pixels to reach a fixed number per line. The non-linearity of mirror velocity and earth rotation result in the skewed or paralleogram outlines of scene. Fractional band offsets are usually the result of false line starts. The data fitting to some standard map projection, using mathematical operations, are also carried out on the data. Universal Transverse Mercator (UTM), Space Olique Mercator (SOM) and Polar Stereographic map projections (for scenes above 65°N and below 65°S) are commonly used. Ground control points are used in this operation.

Line dropout is the effect of momentary voltage fluctuations or loss of signals tied to the electronics or the data transmission system. The missing line data is approximately restored by interpolation in which DN values of adjacent pixels on either side of the dropout line area is used to estimate (average) the most probable value of the intermediate pixel. Re-sampling is carried out on the geometrically corrected data that are spatially displaced. The brightness value for a pixel shifted 100 m by geometrical rectification is not equivalent to the specific radiance value for that spectral band to be expected from this new section of the ground. Using nearest neighbour, bilinear interpolation and cubic convolution methods make an estimate of the new brightness value or DN. Resampling does compromise the original radiometry of the image to some extent.

The reduction in variations of detector response is made prior to launch to match these detectors to a uniform gain and offset response, their behaviour in operation is invariably non-uniform. Thus one or more line in each array of six may in any sweep have higher or lower average radiance values over the entire line length giving rise to an often noticeable striping (lighter or darker tones than neighbour) in individual band images. It is removed by histogram normalization method. Based on the histogram of individual group, an edge test between line pairs is applied to identify bad lines that exceed some threshold criterion. A reference line in the group of six is then used to adjust or normalize deviant lines to new values that most closely approximate the proper DN's.

Atmospheric corrections – The interaction of light with atmospheric gases and particles can produce notable variations in the radiance levels recorded by a remote sensor. Rayleigh and Mie scattering processes give rise to an additional radiance from the atmosphere that increases the overall brightness level at shorter wavelengths. This is accomplished by determining the lowest value from the histogram of brightness value distribution for each band and this value (assumed to be of atmosphere) is subtracted from all other brightness values in the scene. However, sophisticated methods rely on the direct meteorological measurements that are fed into the models for calculating the expected atmospheric spectral radiance under specific weather conditions.

Solar illumination The seasonal changes in sun elevation and azimuth should be adjusted or normalized prior to mosaicing of images. The influence of sun angle is corrected by dividing DN's by the cosine of the elevation angle. The presence of topographic slopes complicates this correction. Since, it is not significant, the features are identified or classified by referring to ground truth. A detailed account of the pre-processing of satellite data can be found in Manual of Remote Sensing (1987). Most of the satellite data receiving stations and supplying agencies carry out these pre-processes prior to supply to the customers. Schematic diagram showing the scan angle of the satellite and solar zenith angle is shown in Fig. 6.16. Specular reflectance from the ground objects vary with texture of the surface (Fig. 6.17).

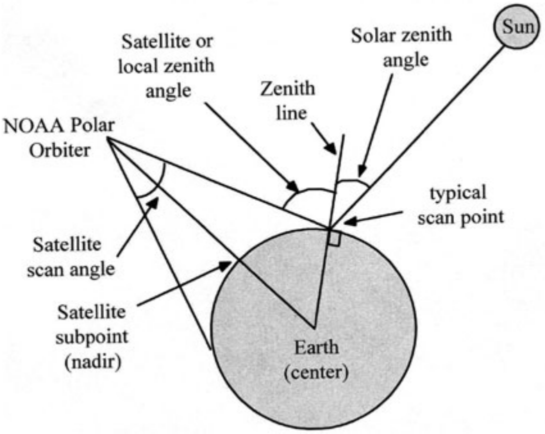


Fig. 6.16: Schematic diagram showing the sun angle position of the satellite and solar zenith angle.

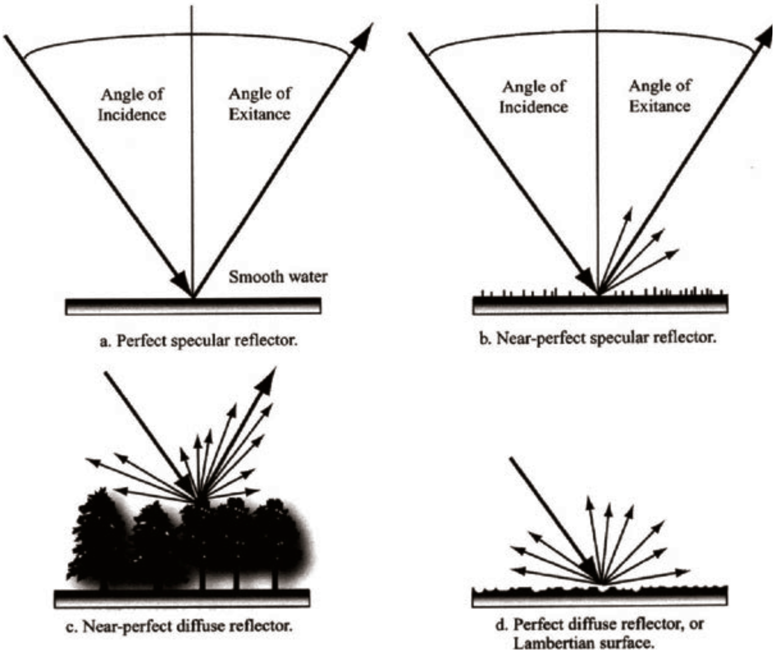


Fig. 6.17: Specular and diffuse reflectance of ground objects.

Contrast Enhancement

Contrast manipulation – Grey level thresholding is used to segment an input image into two classes – one for those pixels having values below an analyst-defined grey level and one for those above this value (Fig. 6.18). *Density slicing* – DN is distributed along the *x* axis of an image histogram divided into a series of analyst-specified intervals of slices. All of the DNs falling within a given interval in the input image are then displayed at a single DN in the output image. Consequently six different slices are established and the output image contains only six different grey levels. Level slicing is used extensively in the display of thermal infrared images in order to show discrete temperature ranges coded by grey level or colour.

Contrast Stretching – Image display and recording devices typically operate over a range of 256 grey levels. Sensor data in a single image rarely extend over this entire image. This stretch is carried out to expand the narrow range of brightness values typically present in an input image over a wider range of grey values. The resultant input image is designed to accentuate the

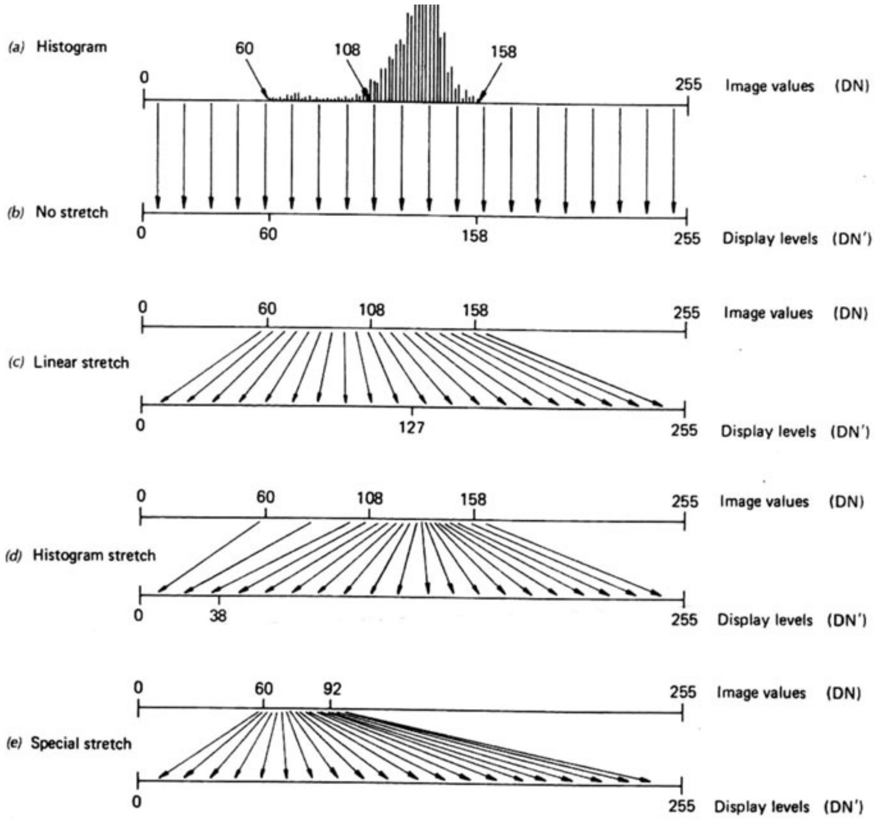


Fig. 6.18: Contrast enhancement techniques.

contrast between the features of interest to the image analyst. One drawback of the linear stretch is that it assigns as many display levels to the rarely occurring image values as it does to the frequently occurring values. In histogram, equalized stretch that improves the frequently occurring portion of the histogram is stretched. Non-linear stretches such as sinusoidal transformations can be applied to image data to enhance subtle differences within homogenous features such as forest stands or volcanic flows. Enhanced colour images can be prepared by applying these procedures to separate bands of image data independently and then combining the results into a composite display. It depends on the nature of digital image scene.

Spatial and Directional Filters

Spectral filters serve to block or pass energy over various spectral ranges, and emphasize or de-emphasize image data of various spatial frequencies (tonal roughness). In operation each pixel tone or grey value is multiplied by the filter weight. The resulting products are then summed up and the sum is divided by the sum of the weights in the filter. This represents the filter-output image-pixel grey value for the centre of the spatial filter. The grey levels in heterogeneous areas change abruptly over a relatively small number of pixels and they represent physical characteristics of the object (Fig. 6.19). Smooth images are those of low spatial frequency, where there is a gradual change in DN. Low pass filters are designed to emphasize low frequency features (large areas in brightness) and de-emphasize the high frequency components of an image. High pass filters do just the reverse. Filtering is carried out in spatial domain by applying filters directly to the image or in

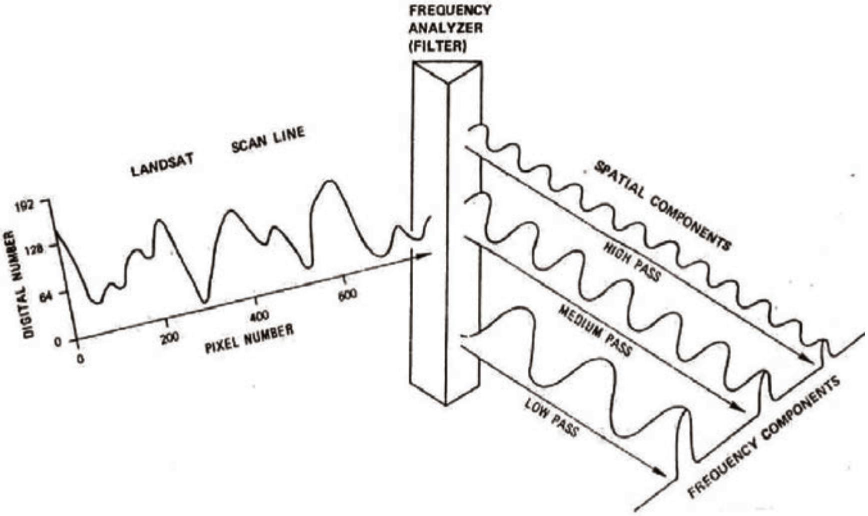


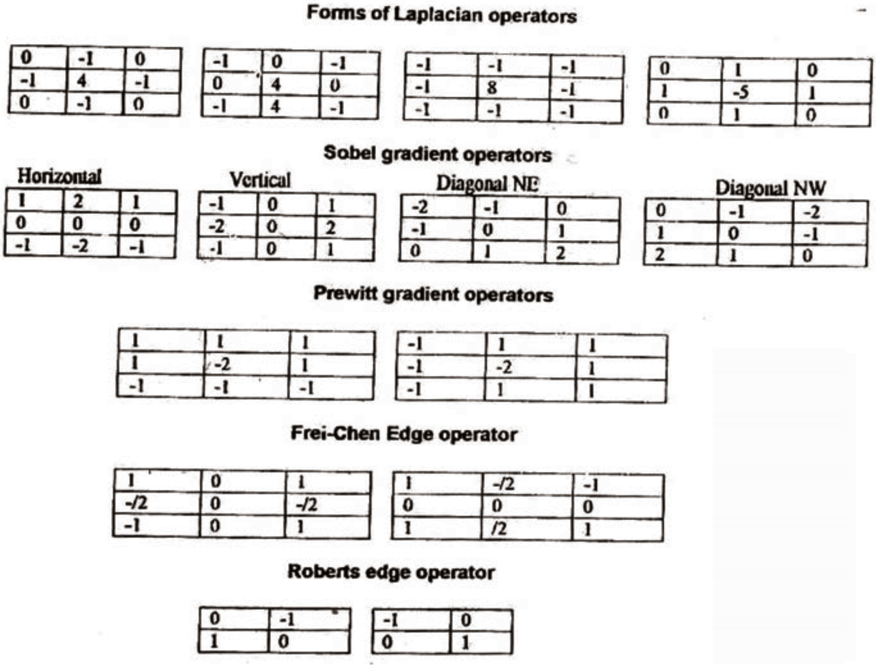
Fig. 6.19: Spatial frequency filtering of digital data.

spatial frequency domain, where the image is transformed to frequency domain by Fourier transformation after which filtering is performed (Joshi, 1998).

Spatial filtering is a local operation wherein pixel values in an original image are modified on the basis of the grey levels of neighbouring pixels. A simple *low pass filtering* may be carried out by passing a moving window through the original image and creating a second image whose DN at each pixel corresponds to the local average within the moving window at each of its positions in the original image. This process is also known as noise suppression. A simple *high pass filter* may be implemented by subtracting a low-pass filtered image (pixel-by-pixel) from the original unprocessed image. The resultant images are contrast stretched. *Convolution* is a special type of generic image processing operation. A moving window is established which contains an array of coefficients or weighing factors. Such arrays are referred as kernel or operators (3 × 3; 5 × 5; 7 × 7). The kernel is moved through the original images and the DN at the centre of the kernel in a second output image is obtained by multiplying each co-efficient in the kernel by the corresponding DN in the original image and adding all the resulting products. The influence of the original image depends on the size of the kernel and the weighing schemes.

Edge enhancement brings out the subtle grey variations. Where the values of adjacent pixels vary by more than predetermined threshold values, the interface is marked on the image display with a contour, a step in the grey scale. *Edge enhancement* is the high pass filter that enhances the local contrast to portray the linear features or edges in the image data. The enhanced images preserve both local contrast and low frequency brightness information. Adding back all or a portion of the grey values in an original image to a high frequency component image of the same scene produces them. The following steps are carried out: (1) The kernel size used to produce this image is chosen based on the roughness of the image; (2) The resultant rough images suggest that a small filter size (3 × 3) and large kernels (9 × 9) for smooth images are effective; (3) All or a fraction of the grey level in each pixel of the original scene is added back to the high frequency component image; and (4) The composite image is contrast stretched.

Directional first differencing is another enhancement technique for edge enhancement. It compares each pixel in an image to one of its immediately adjacent neighbours and displays the difference in terms of the grey levels of an output image. The direction can be horizontal, vertical or diagonal. The first difference would be positive or negative so that a constant (127 for 8-bit data) such as the display value median is normally added to the difference for display purpose. Since the pixel-to-pixel difference is very small, the data in the enhanced image often span a very narrow range about the display value median and contrast stretch must be applied to the output image. The



Forms of Laplacian operators

0	-1	0
-1	4	-1
0	-1	0

-1	0	-1
0	4	0
-1	4	-1

-1	-1	-1
-1	8	-1
-1	-1	-1

0	1	0
1	-5	1
0	1	0

Sobel gradient operators

Horizontal

1	2	1
0	0	0
-1	-2	-1

Vertical

-1	0	1
-2	0	2
-1	0	1

Diagonal NE

-2	-1	0
-1	0	1
0	1	2

Diagonal NW

0	-1	-2
1	0	-1
2	1	0

Prewitt gradient operators

1	1	1
1	-2	1
-1	-1	-1

-1	1	1
-1	-2	1
-1	1	1

Frei-Chen Edge operator

1	0	1
-/2	0	-/2
-1	0	1

1	-/2	-1
0	0	0
1	/2	1

Roberts edge operator

0	-1
1	0

-1	0
0	1

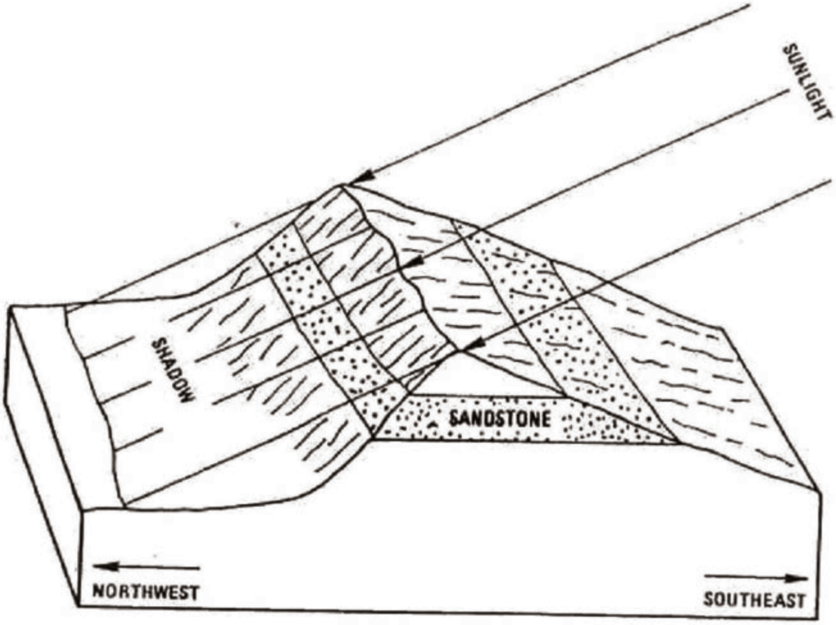
Fig. 6.20: Digital filters used in image enhancement.

filters available for enhancement purpose are shown in Fig. 6.20. Linear filtering operations tend to blur region boundaries and produce the resolution. A non-linear filter that does not blur boundaries is the mode filter. It computes a local spatial-area histogram centered on each pixel and outputs the most frequently occurring value in that small region as the replacement of grey value for the central pixel. Klette and Zamproni (1996) have summarized the image processing operators.

Fourier analysis is another spatial manipulation analysis in the frequency domain. In this approach, an image is separated into its various spatial frequency components through application of a mathematical operation. This operation amounts to fitting a continuous function through the discrete DN values, if they were plotted along each row and column in an image. The peaks and valleys along any given row or column can be described mathematically by a combination of sine and cosine waves with various amplitudes, frequencies and phases. A Fourier Transform results from the calculation of the amplitude and phase for each possible spatial frequency in an image. Two-dimensional scatter plot known as Fourier spectrum is displayed from the separated spatial frequencies. Features trending horizontally in the original image result in vertical components in the Fourier spectrum and features aligned vertically in the original result in horizontal components in the spectrum.

Multi-image Manipulation – Arithmetic Operation

The arithmetic operations are carried out to bring out the feature in question either by addition, subtraction, multiplication, division or combination of operations. *Spectral ratio* is one among the enhancement methods, wherein the DN values in one spectral band is divided by the corresponding values in another band. The DNs observed for each cover type are substantially lower in the shadowed area than in the sunlit area (Fig. 6.21). However, the ratio values for each cover type are nearly identical, irrespective of the illumination condition. Hence, a ratioed image of the scene effectively compensates for the brightness variation caused by the varying topography and emphasizes the colour content of the data. It is useful for discriminating subtle spectral variations in a scene that are masked by brightness variations



SANDSTONE REFLECTANCE

ILLUMINATION	BAND 4	BAND 5	RATIO 4/5
Sunlight	28	42	0.66
Shadow	22	34	0.65

Fig. 6.21: Removal of illumination differences on a ratio image.

in images from individual spectral bands or in standard colour composites. Near-infrared to red ratio for healthy vegetation is normally very high and it is lower for stressed vegetation (As the near-infrared reflectance decreases and the red reflectance increase). It is effectively used in differentiating areas of the stressed and non-stressed vegetation. The advantages of ratio images brings out the material of the same ratio values regardless of variation in illumination over mountains. Disadvantages are the difference in albedo is suppressed. Thus dissimilar materials with different albedo but similar slopes on their spectral reflectivity curves may be inseparable on ratio images (Sabins, 1978).

Band differences and ratios are used to produce vegetation index images from AVHRR data. They are used in vegetation monitoring from different sensors and vegetation conditions. The tasseled cap transformation rotates the MSS data such that the majority of information is contained in two components or features, which are directly related to physical scene characteristics. Brightness is defined as the direction of principal variation in soil reflectance. Greenness is approximately orthogonal to brightness and is a contrast between the near-infrared and visible bands. Brightness and greenness express 95% or more of total variability in the data (Illumination and atmospheric effects are to be normalized). Crist and Cocone (1996) found that six bands of reflected data of Landsat TM effectively are in three dimensions, defining planes of soil, vegetation and a transition zone between them. The wetness is related to canopy and soil moisture. *Transformed Vegetation Index (TVI)* is computed as:

$$\mathrm{TVI} = [\ (\mathrm{DN}_4 - \mathrm{DN}_3/\mathrm{DN}_4 + \mathrm{DN}_3) + 0.5]^{1/2} \times 100$$

where DN_4 and DN_3 correspond to the DNs in band TM3 and TM4 respectively. Ground reference data collected in such areas have shown the TVI to be proportional to the amount of green biomass present within each pixel. TVI levels were colour coded in representing the greenness of the vegetation/crop. False colour composite is also generated from three monochromatic ratio data sets. Selecting a ratio to include in the composite is very difficult. The Optimum Index Factor ranks all possible three-ratio combinations based on the total variance present in each ratio and the degree of correlation between ratios. The combination containing the most variance and least correlation is assumed to convey the greatest amount of information throughout the scene. The overall information content need not convey the specific subject information required by the analyst. A trial-and-error is often necessary.

Principal Components and Canonical Analysis

The inter-band correlation is often encountered in the multi-spectral image data analysis. Principal and canonical transformation techniques remove redundancy in the data. They are applied either as an enhancement operation prior to visual interpretation of the data or as pre-processing procedure before the automated classification. The computational efficiency of the classification process is confined to the reduction in the dimensionality of the original data. A random sample of pixels has been plotted on a scatter diagram according to their grey levels as originally recorded in the bands A and B. Fig. 6.22 shows the PC analysis of remote sensing data. Superimposed on the band A/band B axis system are two new axes that are rotated with respect to the original measurement axes and have their origin at the mean of the data distribution. Axis I defines the direction of the first principal component and axis II as the second principal component. It is calculated as:

$$\begin{aligned} DN_1 &= a_{11}\ DN_A + a_{12}\ DN_B \\ DN_{11} &= a_{21}\ DN_A + a_{22}\ DN_B \end{aligned}$$

where DN_1 and DN_{11} are digital numbers in new (principal component) coordinate system, $DN_{A,}$ DN_B digital numbers in old coordinate system, and a_{11}, a_{12}, a_{21}, a_{22}, are coefficients (constants) for the transformation.

The *Principal Component* data values are simply linear combinations of the original data values. The first principal component (PC1) includes the largest percentage of the total scene variance and succeeding components (PC2, PC3, …, PCn) each contains a decreasing percentage of the scene variance. Successive components are chosen to be orthogonal to all previous ones; the data they contain are not correlated. Principal Component technique is effective where little prior information concerning a scene is available. Ratioed images can be analyzed as a separate black and white image or any three component images may be combined to form a colour composite.

Canonical Component Analysis (CCA) is also referred as multiple discriminant analysis. The canonical component axes in figure (axis II and I)

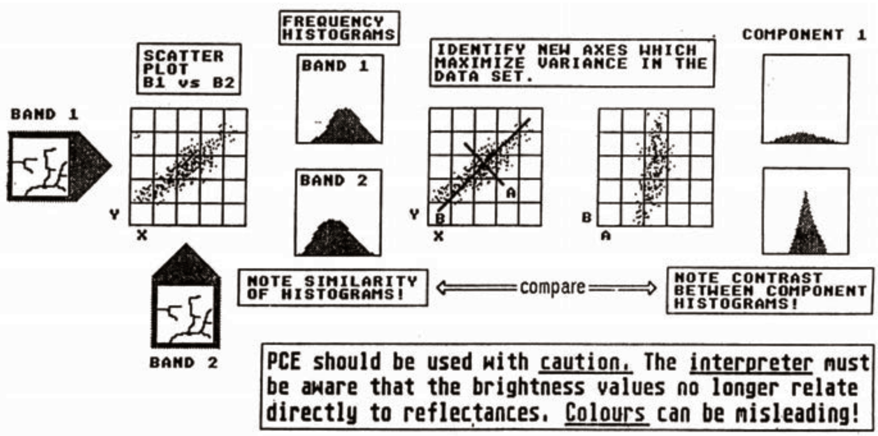


Fig. 6.22: Principal component analysis technique.

have been located to maximize the separability of these classes while minimizing the variance within each class. The axes have been positioned in this figure such that the three feature types can be discriminated solely on the basis of the first canonical component (CCI) values located along axis I.

Intensity-Hue-Saturation (IHS) Colour Space Transformation

The DN values of three different bands are represented by blue, green and red in a colour composite. Here, intensity relates to the total brightness of a colour; hue refers to dominant or average wavelength of light contributing to a colour and saturation refers to the purity of a colour relative to grey. Transformation of RGB components into HIS components before processing provide more control over the enhancement. This approach is called hexacone model and it involves the projection of the RGB colour cube onto a plane that is perpendicular to the grey line and tangent to the cube at the corner farthest from the origin. The distance along the grey line from black to any given hexagonal projection defines this model intensity. Within the appropriate hexagon, the hue is expressed by the angle around the hexagon and saturation by the distance from the grey point at the centre of the hexagon. The farther a point lies away from the grey point, the more saturated the colour. The advantage of these techniques is the ability to vary each HIS component independently without affecting the others. It is used to display spatially registered data of varying spatial resolution. Variables with diverse information content can be represented by different colour attributes that can be perceived. Numerical variations in the image are uniformly represented in variations of perceived colours.

6.10 Image Classification

Multispectral classification is performed using a variety of methods, including algorithms based on *parametric* and *nonparametric* statistics that use ratio and interval-scaled data and *non-metric* methods that can also incorporate nominal scale data; the use of *supervised* or *unsupervised* classification logic; the use of *hard* or *soft* (*fuzzy) set classification* logic to create hard or fuzzy thematic output products; the use of *per-pixel* or *object-oriented classification* logic; and *hybrid* approaches. *Parametric* methods such as maximum likelihood classification and unsupervised clustering assume normally distributed remote sensor data and knowledge about the forms of the underlying class density functions. *Nonparametric* methods such as nearest-neighbour classifiers, fuzzy classifiers, and neural networks may be applied to remote sensor data that are not normally distributed and without the assumption that the forms of the underlying densities are known. *Nonmetric* methods such as rule-based decision tree classifiers can operate on both real-valued data (e.g., reflectance values from 0 to 100%) and nominal scaled data (e.g., class 1 = forest; class 2 = agriculture).

The overall objective of image classification procedures is to categorize all pixels in an image into land cover classes or themes. The multi-spectral data are used to perform the classification based on spectral pattern present within the data for each pixel on the numerical basis of categorization. *Spectral pattern recognition* involves the categorization of pixels based on their spatial relationship with the surrounding pixels. It considers image texture, pixel proximity, feature size, shape, directionality, repetition and context. Temporal pattern recognition uses time as an aid for feature identification. Spectrally-oriented classification uses supervised classification that guides the analyst; and supervise the pixel categorization process by specifying to the computer algorithm, numerical descriptors of the various land cover types present in the scene. Representative sample sites of known cover-type training areas are used to compile a numerical interpretation key. Figure 6.23 shows the schematic diagram showing supervised and un-supervised digital image classification.

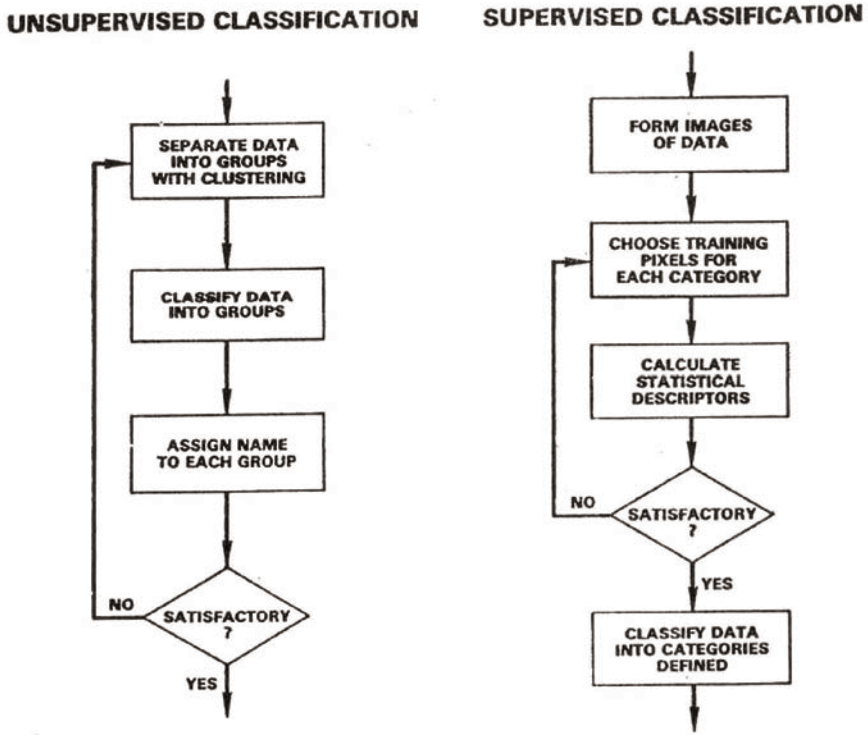


Fig. 6.23: Schematic diagram showing image classification.

Unsupervised Classification

Numerous mathematical approaches to spectral pattern recognition are available. This section describes about the various approaches that are available for our use. Two dimensional digital values or measurement vectors from two bands are attributed to each pixel which may be expressed graphically by plotting them on a scatter diagram. DN of Band 3 is plotted on y-axis and Band 2 is x-axis. Figure 6.24 shows the DN value plotting. These DN locate each pixel value in the two-dimensional measurement space of the graph. If we are aware about the ground conditions then these scatter plots indicate a category to which it belongs. These clouds of points represent multidimensional description of the spectral response pattern of each category of cover type to be interpreted. The following methods use these training set descriptions of spectral response patterns as interpretation key.

In *Minimum Distance to Means Classifier,* the mean or average, spectral value in each band for individual category is determined. These values comprise the mean vector for each category. By knowing the positional coordinates of two-channel pixel, an unknown pixel may be classified by computing the distance between the value of the mean of that category. The unknown pixel is assigned to the closest class and if it is farther than the assigned distance, then it is classified as unknown (Fig. 6.25). This minimum-distance-to-means is mathematically simple and computationally efficient. It is insensitive to different degrees of variance in the spectral response data.

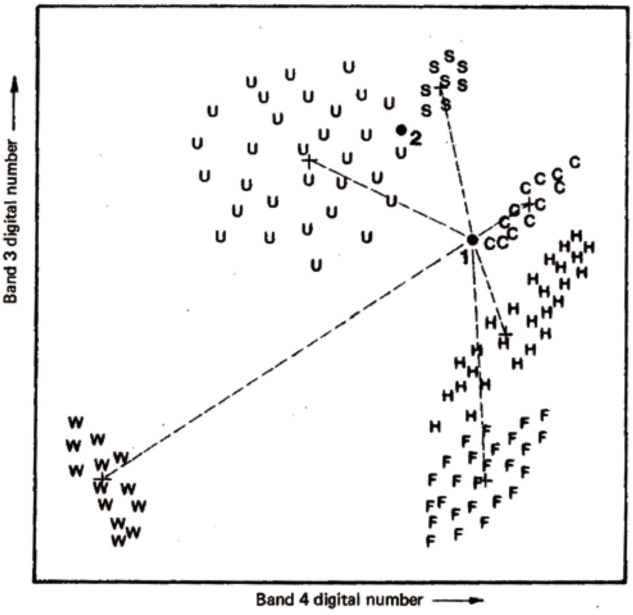


Fig. 6.24: Plotting of DN values.

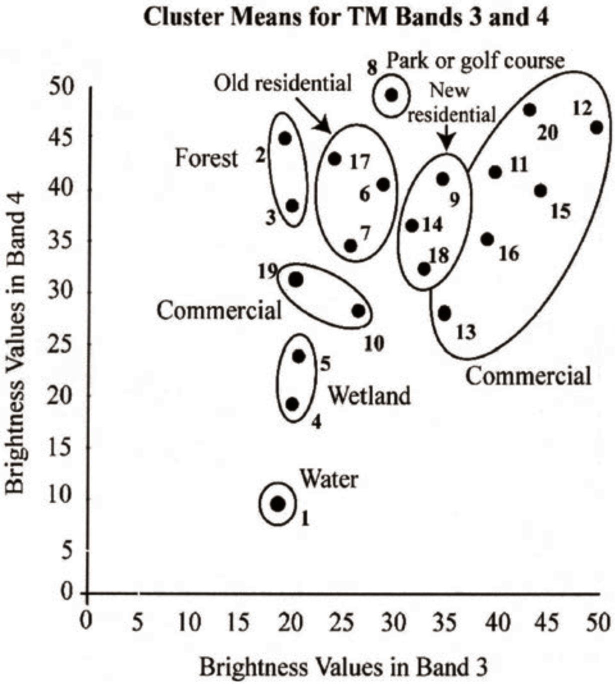


Fig. 6.25: Cluster means method.

The distance between this pixel value and each category mean value is shown by the computed dotted lines. It is assigned to the closest class. This classifier is not attempted when the classes are close to one another in the measurement space. Equi-Probability cluster pixels are used in the classification.

In *Parallelepiped classifier*, the sensitivity to a category variance is introduced by considering a range of values in the training set. It is defined by the lowest and highest number values in each band and appears a rectangular area in two-channel scatter diagram. An unknown pixel is classified according to the category range or decision region in which it lies or as unknown if it lies outside all regions (Fig. 6.26). The multi-dimensional analogs of these rectangular areas are called parallelepipeds. When the category ranges overlap each other, then it is arbitrarily classified as one category or not sure. The insensitivity to covariance would cause pixel 1 to be classified as class 1 instead of class 2. Overlap is caused largely because the rectangular decision regions poorly describe category distributions exhibiting correlation. Correlation is the tendency of spectral values to vary similarly in two bands, resulting in elongated, slanted clouds of observations on the scatter diagram.

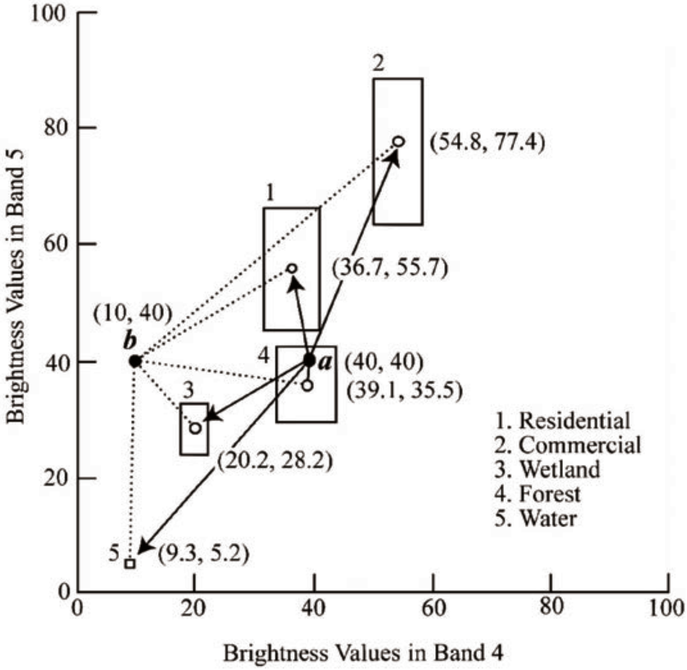


Fig. 6.26: Parallelepiped classifier.

Maximum likelihood classifier evaluates both the variance and covariance of the category spectral response patterns when classifying an unknown pixel. It is assumed that the cloud of points forming the category training data is Gaussian (normally distributed) in nature. This assumption is generally reasonable for common spectral response distributions (Fig. 6.27). The distribution of a category response pattern can be completely described by the mean vector and covariance matrix. This classifier delineates ellipsoidal equi-probability contours. The shape of the equi-probability contours expresses the sensitivity of the likelihood classifier to correlation. Given these parameters, we can compute the statistical probability of a given pixel value being a member of a particular land cover class. The probability values are plotted in a three-dimensional graph. The resulting bell-shaped surfaces are called probability density function and there is one such function for each spectral category. This function is used to classify an unidentified pixel by computing the probability of the pixel value belonging to each category.

Bayesian classifier is the extension of maximum likelihood approach. It applies weighing factor to the probability estimate. The analyst determines the a priori probability or the anticipated likelihood of occurrence for each class in the given scene. A weight associated with the cost of miscalculation

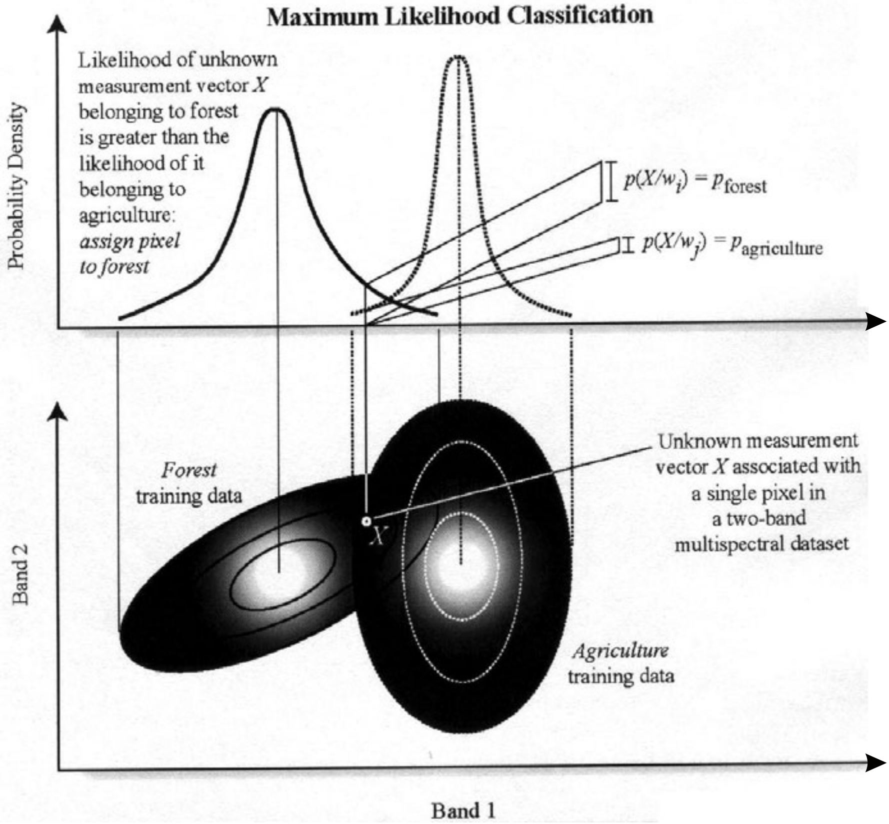


Fig. 6.27: Maximum likelihood classifier.

is applied to each class. The effects of the said factors achieve the optimum classification. In practice, the classification is performed with an assumption that equals probability occurrence. The principal drawback of the maximum likelihood classification is the large number of computations required to classify each pixel. It is computationally much slower than other techniques. Several approaches have been attempted to increase the efficiency of this method such as implementation of look-up table, reduce dimensionality of data set, identify all possible combinations etc.

Supervised Classification

The classes that result from unsupervised classification are spectral classes that have to be compared with the ground observations for its theme. In the supervised classification, we define the information categories and then examine their spectral separability (Fig. 6.28).

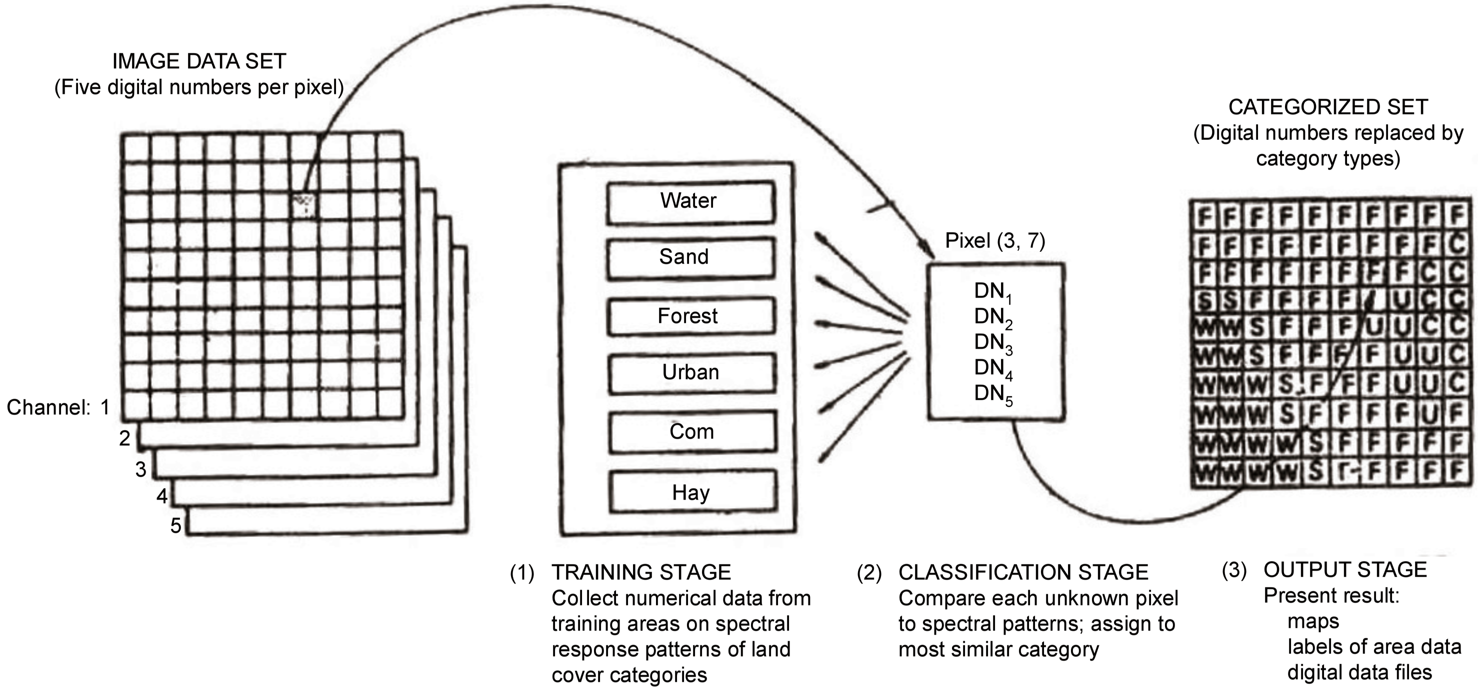


Fig. 6.28: Supervised classification.

6.11 Post Classification Processes

Classified data often manifest a salt-and-pepper appearance due to the inherent spectral variability encountered by a classifier when applied on a pixel-by-pixel basis. In such situations, it is desirable to smooth classified output. The low-pass filtering cannot be applied, because the image classification is an array of pixel locations containing numbers serving the function of labels and not quantities. A smoothing algorithm on the basis of logical operations is needed. The *majority filter* that operates on a moving window (3 × 3) is passed through the classified data set and determines the majority classes. If there is no majority class in the window then the identity of the centre pixel is not changed. As the window moves through the data set the original class codes are continually used and not the labels that are modified from the previous window position. This filter can also incorporate some form of class and/or spatial weighing function. The data may be smoothed more than once.

Classification Accuracy

There is no simple, standardized, generally accepted methodology for determining classification accuracy of land cover features derived from remote sensing data. However, the ability to produce digital land cover classifications far exceeds the ability to meaningful accuracy. There are two methods of accuracy evaluation such as: homogeneous test areas selected by the analyst and test pixels or area selected randomly. If the training areas are homogeneous and they are spectrally separable, then the classification strategy employed works well. There is a need to *refine the process of training set* selection. A subset of the training sets may be withheld for post classification accuracy assessment, again using a contingency table to express the results. The accuracy represents at least first approximation to classification performance throughout the scene. Random sampling of pixels circumvents the above problems, but plagues with its own set of limitations. Collection of reference data for large sample of randomly distributed points is often difficult. The random sampling depends on the ability to precisely register the reference data to the image data. The random classifier will produce percentage correct values in a contingency table. The kappa or KHAT index ranges between 0 and 1 and expresses the proportionate reduction in error achieved by a classifier as compared with the error of a completely random classifier. Thus, a value of 0.75 would indicate that the classifier was avoiding 75% of the errors that a totally random process would have produced. Sample size should also weigh heavily in the development and interpretation of classification accuracy figures. The quality of any accuracy estimate is only as good as the information used to establish the true land cover types present in the test site. Some estimate of the errors present in the reference data should be incorporated into the accuracy assessment process. The accuracy assessment procedure must be designed to reflect the intended use of the classification.

6.12 Multi-sensor Data Merging

The spectral and spatial content of different sensors are merged to derive a product that has both the information content of the sensors and scaling. Images from different sensors and dates are registered and all of the image data from various dates are used in the classification process. The images should be geometrically corrected and sampled into 50 m UTM grid, so that they can be precisely registered, pixel-by-pixel on a common geographic base. The composite data could be used for automated classification or for generation of range of multi-date composite images. Multi-temporal approach is best suited for crop classification. Here, the classification is based on physical modelling of the time behaviour of each crop's spectral response pattern. Hence the greenness at any time t can be modelled in terms of peak greenness G_m, the time of peak greenness t_p and the width σ of the profile between its two reflection points. The G_m, t_p and σ account for more than 95% of the information in the original data and can therefore be used for classification instead of the original spectral response patterns. The spatial resolution of PAN and spectral content of LISS are merged and shown in Fig. 6.29.

Change Detection Procedures

The multi-temporal data sets are used to discriminate area of land cover change between two dates of imaging. The one way of discriminating changes between two dates of imaging involves independently classifying each image; registering the results and locating those pixels that have changed their land cover classification between dates. Another method is to register two images and prepare a temporal difference image by subtracting the DNs for one date from those of the other. Alternatively a temporal ratio image can be used with data from two dates being ratioed rather than subtracted. Ratios for areas of no change tend towards one and areas of change will have higher or lower ratio values. The analyst has to find a meaningful change-no change threshold within the data.

Data Fusion

Multi-spectral image data fusion is a process that generates synthetic images from combination of primary images, by attempting to preserve the best

Fig. 6.29: IRS image showing Spectral (LISS) and spatial (PAN) resolution fusion.

characteristics of each primary image. The integration of different data sources can be divided into major categories, viz. sensor dependent and independent. The augmentation of data from one sensor with that from another sensor and treating the entire data as one extended set could be carried out provided they have similar radiometric range physical principles of data gathering. In the sensor-dependent approach the regional boundaries produced from visible/ infrared images of IRS can be merged with SAR images. Landsat TM colour composite image and air-borne/satellite radar image can be merged to create colour-infrared-radar combinations. STAR-1 radar data is a X band synthetic aperture, data with HH polarization and a resolution of 6 × 6 m. Landsat data were re-sampled into 6 × 6 m cell size for registration with the radar data. This data combination will take advantage of the spectral resolution of Landsat TM and the spatial resolution and side-lighting characteristics of radar data to produce a composite image that offers potentially greater interpretability than an image from either sensor alone. Air-borne radar image is fused with gamma ray spectrometer data after re-sampling as shown in Fig. 6.30.

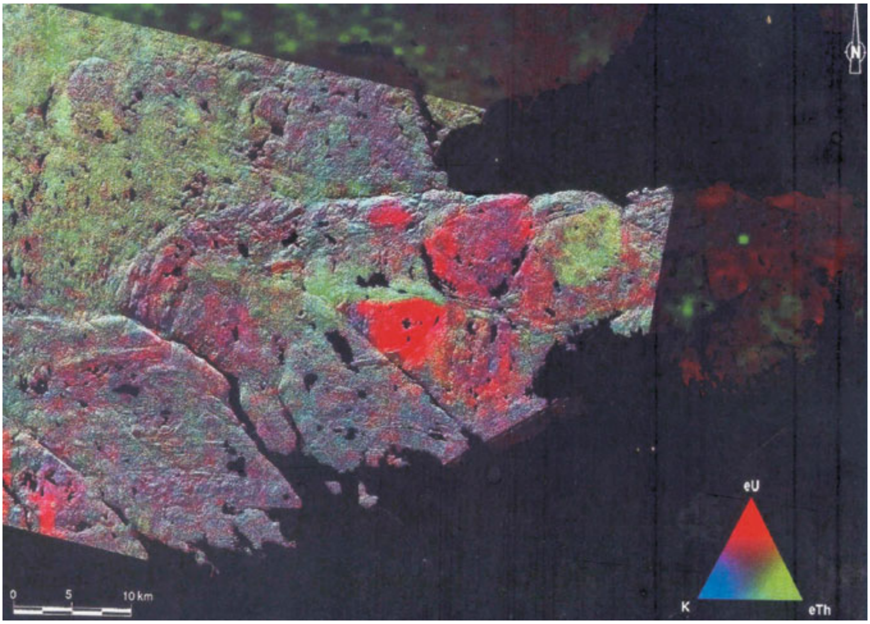


Fig. 6.30: Combination of air-borne radar and gamma-ray spectrometer data. (eU: uranium, K: potassium, eTh: thorium).

Courtesy: Energy, Mines & Resources Canada

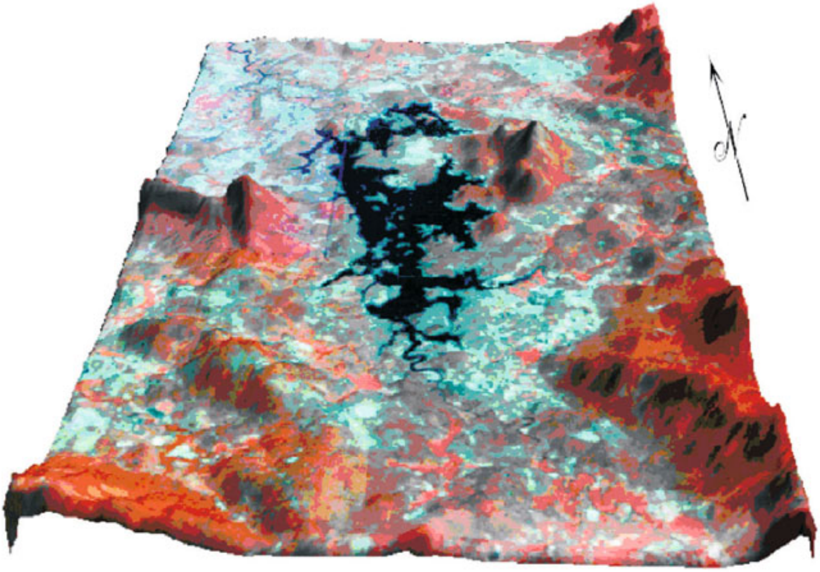


Fig. 6.31: FCC image draped over the DEM to show the variation in vegetation cover.

Data merger employed in digital image processing is the registration of image data with non-image or ancillary data sets. This could vary from soil type elevation to assessed property valuation. The ancillary data should be amenable to accurate geo-coding. Digital elevation model can be registered with Landsat or IRS data. NDVI image is draped over the DEM to show the variation in vegetation cover of Goa in Fig. 6.31.

6.13 Indices for Drought Analysis

Vegetation Indices

Chlorophyll and cartenoid pigments in plant tissues absorbs light in the visible red (AVHRR channel 1) while mesophyll tissue reflects light in the near-infrared (AVHRR channel 2) wavelengths (Tucker and Sellers, 1985). Hence, a healthy and actively photosynthesizing plant will therefore look darker in the visible and brighter in the infrared region than an unhealthy or dead plant. The early vegetation index was estimated by a simple ratio of channel 2 over channel 1 reflectance. Table 6.4 shows the different vegetation indices used in the vegetation cover mapping using remote sensing data. Normalized Difference Vegetation Index (NDVI) has overcome the problem of reflectance from the (usually dark or reddish) soil background by dividing the difference between these two channels by their sum. It is defined as:

$$\text{NDVI} = \text{Ch2} - \text{Ch1}/\text{Ch2} + \text{Ch1}$$

The values theoretically range between –1 and +1 but in practice well within these limits. Even though NDVI is a specific measure of chlorophyll abundance and energy absorption, it has been extended to cover vegetation biomass (Tucker et al., 1986), coverage and phenology in a range of ecosystem. It is highly useful in areas of sparse vegetation coverage where they have a better range. It covers the full area including forests. It is not ideal because of continuing problems with background soils (which are darkened by rainfall) and differential atmospheric effects on the readings in Ch1 and Ch2 (atmospheric aerosols scatter light particularly in Ch1, whilst atmospheric water vapour absorbs particularly in Ch2). A large NDVI index value corresponds to areas of evapotranspiration rates which represent dense vegetative cover, permeable soil and substantial soil moisture. A small index value corresponds to areas having minimal evapotranspiration that represents bare ground or little vegetation, relatively impermeable soils and minimal soil moisture. Spatial variation in NDVI of Jhod nadi test site, Maharashtra, India is shown in Fig. 6.32. Display of smaller index values (0.21-0.25) is attributed to agriculture region. The seasonal potential for evapotranspiration in agriculture areas would be expected distinctly less than that of the native

Table 6.4: Commonly used vegetation indices

Vegetation Indices	*Formula*
Difference Vegetation Index (DVI)	Nir – Red
Ratio Vegetation Index (RVI)	Nir/Red
Normalized Difference Vegetation Index (NDVI)	(Nir – Red)/(Nir + Red)
Perpendicular Vegetation Index (PVI)	$(1 / (a^2 + b^2)) \times (NIR - aRED - b)$
Soil Adjusted Vegetation Index (SAVI)	$\{(NIR - RED)\ (1 + L)\}/\ (NIR + RED + L)\quad L = 0.5$
Transformed Soil Adopted Vegetation Index (TSAVI)	$(aNIR - bRED + b)/\ \{(aNIR + RED - ab + X(1+ a^2)\}$
Weighed Difference Vegetation Index (WDVI)	NIR – C × RED: C = NIR(bare soil)/ RED (bare soil)
Vegetation Condition Index (VCI)	$(NDVI_{max} - NDVI)/NDVI_{max} - NDVI_{min})$
Transformed Vegetation Index (TCI)	(NDVI + 0.5) ** 0.5
Green Vegetation Index (GVI)	–0.29 MSS 1 – 0.5622 MSS 2 + 0.6 MSS 3+ 0.491 MSS 4
Stress related TM based vegetation indices	STV 11 = (TM 5 × TM 3)/TM 4 STV 12 = TM 4/TM 3 + TM 7 STV 13 = TM 4/TM 3 + TM 5
Mid Infra-red stress related vegetation Index	MSV 11 = TM 4/TM 5 MSV 12 = TM 4/TM 7 MSV 13 = TM 4/TM5 + TM 7
Stress Degree Days (SDD)	$\Sigma\ (T_c - T_a)$

vegetation. The decrease in transpiration during droughts generally is greater in agricultural areas because crops die or their foliage is severely stunted during prolonged drought (Hanson, 1991).

Temperature Condition Index (TCI) derived from AVHRR's thermal channels have increased the accuracy of drought monitoring and also helped in explaining the temperature contribution in the analysis of drought genesis and monitoring (Kogan, 1995). *Soil moisture* is a key variable in controlling the exchange of water and heat energy between the land surface and the atmosphere through evaporation. Simulations with numerical weather prediction models have shown that improved characterization of surface soil moisture, vegetation and temperature can lead to significant forecast improvement. Quantitative measurements of soil moisture in the surface

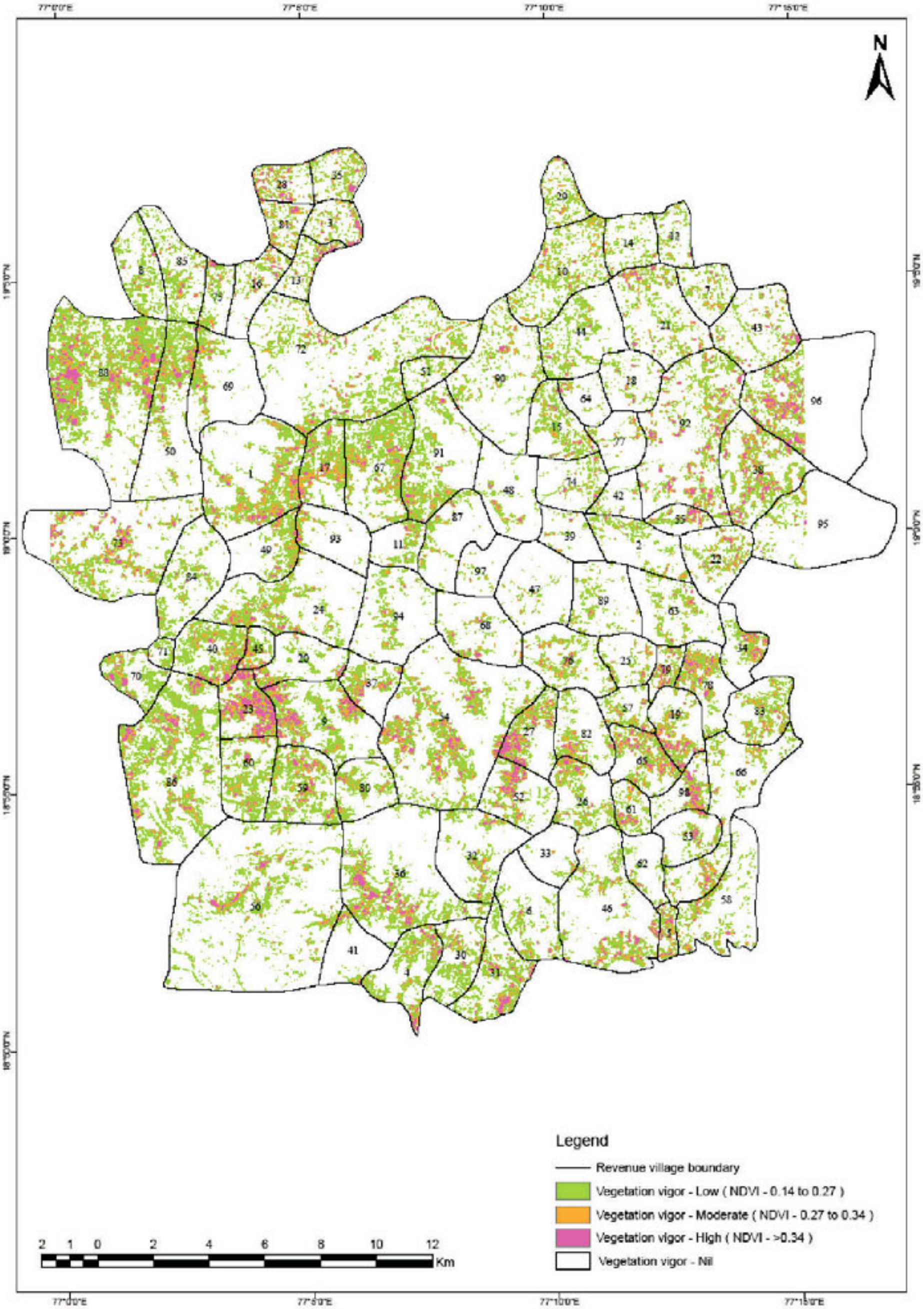


Fig. 6.32: NDVI image showing healthy green vegetation – Loha region.
Source: IRS-P6 LISS-3 image of January 5, 2006

layer of soil have been most successful using passive remote sensing in the microwave region. The potential exists today to retrieve soil moisture estimates from space-based instruments at frequencies of about 6 GHz (C band). However, at frequencies between 1 and 3 GHz (L band) are best suited for detection of soil moisture because energy is emitted from a deeper soil layer and less energy is absorbed or reflected by vegetation. The S (2.65 GHz) and L (1.413 GHz) band microwave radiometer (SLMR) is a dual-frequency passive sensor system. In addition a six-channel stepped frequency (4.63, 5.06, 5.91, 6.34, 6.77, 7.20 GHz) single polarization C band radiometer was used. Automatic soil profile and radiation measurement systems were installed on each plot to provide continuous measurements of soil moisture and temperature profiles and other hydrological variables.

Global Vegetation Index (GVI) is estimated from the radiance from VIS (Ch1 0.58-0.68 μm), NIR (0.72-1.1 μm) and two thermal bands (Ch4 10.3-11.3 μm and Ch5 11.5-12.5 μm) of NOAA satellites. Changes in viewing geometry can lead to both an increase and decrease in NDVI, depending on the location, type of vegetation and illumination. Orbital drift, sensor degradation and satellite change create long-term noise in NDVI data observed when the satellite is more than three years in the orbit. The AVHRR data of China showed that the yield reduction could be attributed to vegetation stress in the main cotton growing areas. Drought-related vegetation in the principal cotton farming area was also observed in 1990. But the unusual weather feature of 1994 was the intensive pre-season drought, which resulted in a deficient water supply for irrigated cotton. Fortunately this deficit was partially offset by a near-normal summer rainfall. Therefore, 1995 stress was much less intensive over a smaller area and resulted in an insignificant cotton yield reduction compared to 1992. Unlike 1992 and 1994, the 1995 AVHRR derived vegetation stress in the cotton growing area was estimated to be non-drought related because the values of the VCI were very low and those of the TCI very high.

Soil Adjusted Vegetation Index (SAVI) effectively adjusts the intercept of the relationship between Ch2 and Ch1 data and minimizes the interference from the soil background.

$$\begin{aligned} \mathrm{SAVI} &= \mathrm{Ch2} - \mathrm{Ch1/Ch2} + \mathrm{Ch1} + L \\ &\qquad (\text{or NDVI})\ (1+L)/[(1+L/(\mathrm{Ch2}-\mathrm{Ch1})] \end{aligned}$$

where L is a weighing parameter that varies with vegetation coverage, viz. 1.0, 0.75 or 0.25 for sparse, moderate and densely vegetated conditions.

Global Environment Monitoring Index (GEMI) attempted by Pinty and Verstraete (1992) to reduce the variability introduced by the soil background and atmospheric effect. It gives more constant index of vegetation activity against a much wider range of soil conditions. It is defined as follows:

$$\text{GEMI} = [x\,(1 - 0.25x)] - [(\text{Ch1} - 0.125)/(1 - \text{Ch1})]$$

where $x = [(\text{Ch2}^2 - \text{Ch1}^2) + (1.5\ \text{Ch2}) + (0.5\ \text{Ch1})]/[\text{Ch2} + \text{Ch1} + 0.5]$

The initial application of GEMI to AVHRR data for Africa suggests a three-fold advantage over NDVI such as: (1) less sensitive to atmospheric variations, (2) enhanced ability to detect clouds (appears dark on NDVI and GEMI) which are easily detected and screened out and (3) higher dynamic range in xeric environments showing details (geological formations or land surface topology) in sparsely vegetated areas that are not visible in other imagery (Flasses and Verstraete, 1994).

Direct modelling approach is another method of using vegetation indices for drought analysis. Modelling the spectral response of a surface can take a number of different forms from theoretically based models and the use of radiative transfer and geometric optics to more empirically based models. This attempt was made by Rosema et al. (1992), Hall et al. (1995) and others for forest canopies. Modelling vegetation in an arid environment should have advantages over a similar task in a tropical or temperate environment because of sparse and fairly uniform shape. A common geometric shape (sphere or cone) can be assumed and the proportion of shadow is easily calculated. Due to single plants on a soil background, multiple scattering between different canopy layers can be ignored. Jasinski (1996) has developed a hybrid model using a physical modelling approach to interpret the information in the red/near-infrared feature space derived from a single multi-spectral satellite image. The canopy is considered as geometric elements randomly positioned on a horizontal soil surface. Using a reflectance model, the reflection of a given pixel can be described in terms of canopy transmittance and proportion of illuminated and shaded canopy and illuminated and shaded background.

$$\rho(\lambda) = [m_i + m_s\,\gamma(\lambda)]\ \{\rho\infty(\lambda)[1-\tau^2(\lambda) + \rho g_i(\lambda)\ \tau^2(\lambda)]\} + \rho g_i(\lambda)\ [g_i + g_s\,\tau(\lambda)]$$

where λ is the wavelength of the band centre; m_i – fraction of illuminated canopy, m_s – fraction of shaded canopy, g_i – fraction of illuminated ground, g_s – fraction of shaded ground, $\gamma(\lambda)$ – bulk canopy transmittance, τ^2 – illuminated ground reflectance; and $\rho\infty(\lambda)$ canopy reflectance at zero transmittance. Within this equation, each reflectance term is considered to have a random or poison distribution. This moves away from the commonly made assumption of constant end members and takes account of spatial variability relating to differences in soil texture, organic content, soil moisture, canopy height and leaf area. Treating plants as randomly distributed objects on a planar surface allows the estimation of ground shadow g_s, in terms of a non-dimensional solar geometric similarity parameter equating to the ratio of the mean shadow area cast by a single tree to the mean projected area.

$$g_s = 1 - m - (1 - m)^{+1}$$

m_s is similarly defined in terms of a constant that is derived from plant geometry and the solar zenith angle. The values for bulk transmittance and zero transmittance are estimated using values held in the red/near-infrared scattergram. This model estimates the invariables in equation and uses them to predict lines of constant canopy cover. This method is invertible and little or no ground information is needed.

Thermal Brightness

The theoretical concept of a black body is used to describe a material that absorbs and emits radiation perfectly at all wavelengths. Such material has an emissivity coefficient of 1.0. Black bodies emit radiation only as a function of temperature, the relationship formalized in Planks law (Monteith and Unsworth, 1990). Thermal brightness temperature measured by the satellite is also affected by absorption characteristics of atmospheric constituents (particularly water vapour, ozone, carbon dioxide and aerosols) as well as emission of radiation by the atmosphere itself. Surface temperature and Ch4 and Ch5 brightness temperature that takes into account the emmissivity value of land surface is as follows:

$$\begin{aligned} T_s &= T_{b4} + [\,3.33(T_{b4} - T_{b5})\,(3.5 + E_4/4.5)] \\ &\quad + [(0.75\ T_{b4})\,(E_4 - E_5)] \end{aligned}$$

where T_s is surface temperature; T_{b4} – Channel 4 brightness temperature; T_{b5} – Channel 5 brightness temperature; E_4 – emissivity at Channel 4 wavelength; and E_5 is emissivity at Channel 5 wavelength.

This algorithm was found to be accurate to +3°C for a uniform tall grass prairie habitat in Kansas, when a constant emissivity was assumed. The satellite infrared sensors record different brightness temperatures of each object in the environment. This view is also affected by the reflectance of incident solar radiation (affected by emissivity) as well as the attenuation of the signal by the continuously changing atmospheric column. The difference between soil and air temperatures results in a flow of thermal energy between them, which produces atmospheric effects that result in both local and regional mixing of bodies of air at different temperatures. Further research is in progress about the relationship between vector demographic rates and contemporary thermal IR satellite data independently of ground-based meteorological records.

Albedo Index

It is defined as the ratio of the amount of electromagnetic radiation reflected by a body to the amount incident upon it, often expressed as percentage. The albedo measurement is an additive function of the reflectance in each band

and thus integrates the reflectance of the terrain over the wavelength region sensed by the multi-spectral scanner. This reflected amount is corrected for atmospheric scattering by subtracting from each pixel the darkest value in each band in the scene and by correcting for solar elevation. The corrected value is ratioed with the incoming solar radiation in the same wavelength interval to arrive at the albedo (Robinove et al., 1982). This technique assumes that the percentage of light reflected from the ground (along with cover) would increase if the cover decreases and decreases if it increases. Higher vegetation density, soil moisture, erosion and flash floods will lighten the ground. The following equation can be used:

$$\text{Albedo} = \pi/I \sin \alpha \times (B_4/G_4 + B_5/G_5 + B_6/G_6 + B_7/G_7)$$

where I is total solar irradiance in the four bands; α – sun angle from the horizontal; B_4 – pixel value of band 4 and G_4 is gain in digital counts per unit radiance (from the calibration of the multi-spectral scanner). This equation has not considered any atmospheric corrections.

Evapotranspiration Estimation

Evapotranspiration and the surface albedo are important in the water balance studies and climate changes. The concept of using remotely sensed surface temperature in evapotranspiration has been demonstrated by Bartholic et al. (1972). Brown (1974) calculated the evapotranspiration based on the surface temperature and the air temperature. Surface temperature can be acquired directly from the ground measurements which cannot be generalised since it varies from one type of surface to another. Satellite measurements are not subject to arbitary extrapolation. They are area averaged rather than point values and can be acquired on a regular temporal basis. The surface emissivity is estimated on a pixel scale through satellite data. We can have effective mean emissivity by using the known cover type through NDVI estimation. It is assumed that NDVI is taken as pure vegetation and bare pixels obtained from the reflectance in NIR and red channels and using the information for the calculation of vegetation cover.

$$\text{NDVI} = (\varphi_2 - \varphi_1)\ (\varphi_2 + \varphi_1) \tag{1}$$

where φ_2 and φ_1 are the reflectance measured in red and NIR wavelength. Considering a mixed pixel with vegetation cover P_v and a soil proportion $(1 - P_v)$, the NDVI value (I) as a first approximation is

$$I = I_v P_v + I_g (1 - P_v) \tag{2}$$

where I_v and I_g are the vegetation and ground NDVI values respectively. The vegetation fraction can be obtained from NDVI by inverting the above equation. A mixed pixel reflectance is

$$\varphi_n = \varphi_{nv} P_v + \varphi_{ng} (1 - P_v) \tag{3}$$

where n = 1 for red and n = 2 for near-IR. Substituting equations the NDVI becomes

$$I = P_v (\varphi_{2v} - \varphi_{1v}) + (1 - P_v) (\varphi_{2g} + \varphi_{1g})/P_v$$
$$(\varphi_{2v} + \varphi_{1v}) + (1 - P_v) (\varphi_{2g} + \varphi_{1g}) \tag{4}$$

where φ_{2v} and φ_{1v} are reflectances in NIR and red region for pure vegetation pixels and φ_{2g} and φ_{1g} are reflectances in NIR and red region for pure soil pixels. Depending on the reflectance values of each surface, the correction to equation will be different.

$$I = I_v P_v + I_g (1 - P_v) + d_I$$

where d_I is correcting factor obtained by substracting equations 2 and 4. The proportion of vegetation is calculated using the Valor and Caselles (1996) relation.

$$P_v = (1 - I/I_g)/((1 - I/I_g) - k (1 - I/I_v)) \tag{5}$$

where $k = (\varphi_{2v} - \varphi_{1v})/(\varphi_{2g} - \varphi_{1g})$

The relationship between emissivity (ε) and NDVI of a given surface is

$$\varepsilon = a + b$$

where $a = (\varepsilon_v - \varepsilon_g)/(I_v - I_g)$ and $b = (\varepsilon_g (I_v + dI) - \varepsilon_v (I_v - I_g))/(I_v - I_g) + dI)$

For a given area the coefficient "*a*" is constant while coefficient "*b*" changes from pixel to pixel with the type of vegetation cover and surface structure. Land surface temperature has been calculated by converting the thermal radiance values using inverse Planck's equation

$$T_s = C_2/\lambda \text{ In } [\varepsilon C_1 \lambda^{-5}/\pi L_\lambda] + ! \tag{6}$$

where C_1 is 3.742×10^{-16} W/m^2, $C_2 = 0.0144$ mK, λ = wavelength in m, ε = emissivity and L_λ is spectral radiance.

This model is used to estimate evapotranspiration from remotely sensed and agrometeorological data derived from surface energy balance equation applicable to most land surface as shown by

$$R_n = G + H + LE$$

where R_n is the net radiation flux, LE – latent heat flux commonly called as evapotranspiration (ET), H – the sensible head flux and G is the soil heat flux.

$$ET = (1 - A)\ Rs = 1.24\ \sigma\ (e_a/T_a)^{1/7} \tag{7}$$
$$T_a^4 - E_s\ \sigma\ T_s^4 - \rho\ C_p\ (T_s - Ta)/r_a$$

Surface albedo is estimated between 0.52 and 0.90 μm by the following expression of Goita and Royer (1992).

$$A = {}^{n}\Sigma_{I=1}\ \varphi_I\ Ei/{}^{n}\Sigma_{I=1}\ Ei \tag{8}$$

where φ_I is corrected reflectance of the pixel in the band 'I', E_I – the solar illumination outside the atmosphere in the band 'I' and *n* is the number of bands used (three bands green, red and IR). The reflectance in the band 'I' at the satellite level can be estimated by the expression

$$\varphi_I = \pi\ L\ \lambda\ d^2/E_0 \cos\theta_s \tag{9}$$

where L λ is the apparent radiance, d^2 – sun to earth distance correction factor, E_0 – exoatmospheric solar irradiance and θ_s is solar zenith angle.

In the absence of measured emissivity values, mean value of 0.914 for bare soil and 0.986 for vegetation in 8-14 μm region (Carnahan and Larson, 1990) can be taken. Vegetation structures of crop ($\varepsilon = 0.986$), fallow land ($\varepsilon = 0.971$) and plantation ($\varepsilon = 0.978$) can be considered. The proportion of vegetation cover can be calculated from equation (6). Surface emissivity per pixel is evaluated from equation (7). Surface temperature is estimated from equation (8) mentioned above. The temperature of water surface is 25-26° C over water surface, 41° C over urban area and 26-28° C over vegetation canopies by Kant and Badrinath (1998).

6.14 Temporal Analysis

Surface vegetation cover and hydrological features change with season and their spatial distribution due to the cultivation practices. Crop production and water resources estimation is one among the much sought information for strategic planning. Monitoring of plant growth status and availability of water from surface storage and ground water at different ground resolution (1 m to 30 m) is used for this purpose depending upon the requirement. Seasonal changes are attributed to growth or no growth on the surface and the incident sun angle. An assessment of healthiness of crop is used in the crop production estimate. Figures 6.33 and 6.34 show the revenue village boundaries of Loha test site over IRS false colour composite images April (summer) 2006 and September (winter) 2001 respectively. Crop healthiness (red) along the drainage lines could be seen. Green colour indicates the moisture content/grassy growth could be clearly seen from these images. Figure 6.35 shows the cadastral map of Pardi village over IRS FCC image of April 2006. The window of the original image was stretched to 1:10,000 to match the cadastral map.

Spectral characteristics of surface cover are a reliable tool in classifying the phenological growth of the crops/plants. Dynamic changes of the crop

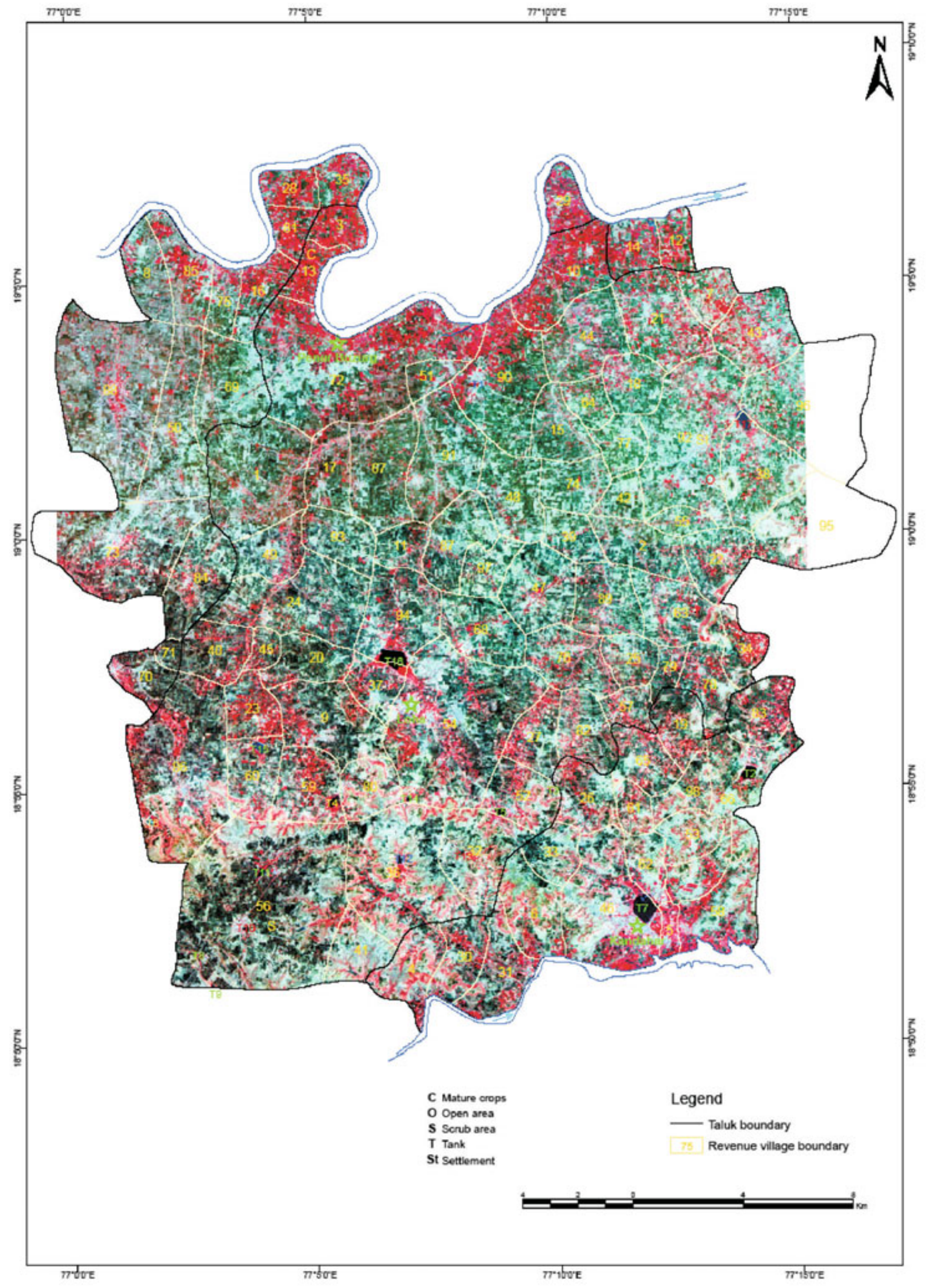


Fig. 6.33: Revenue village boundary of test site over IRS FCC – Dry condition.
Source: IRS-P6 LISS-3 image of April 11, 2006

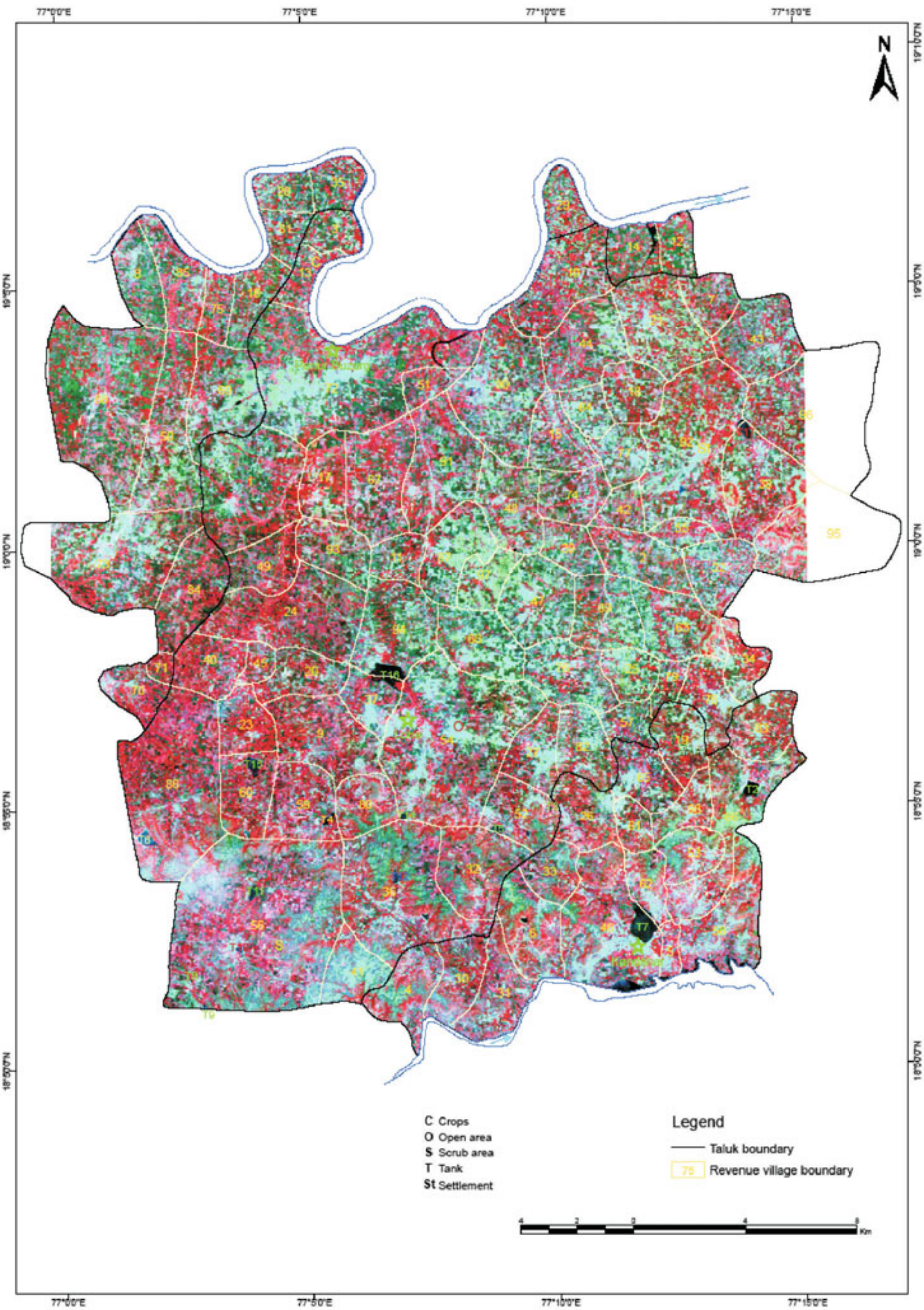


Fig. 6.34: Revenue village boundary of test site over IRS FCC – Wet condition.

Source: Village maps IRS-1C LISS-3 image of April 28, 2001

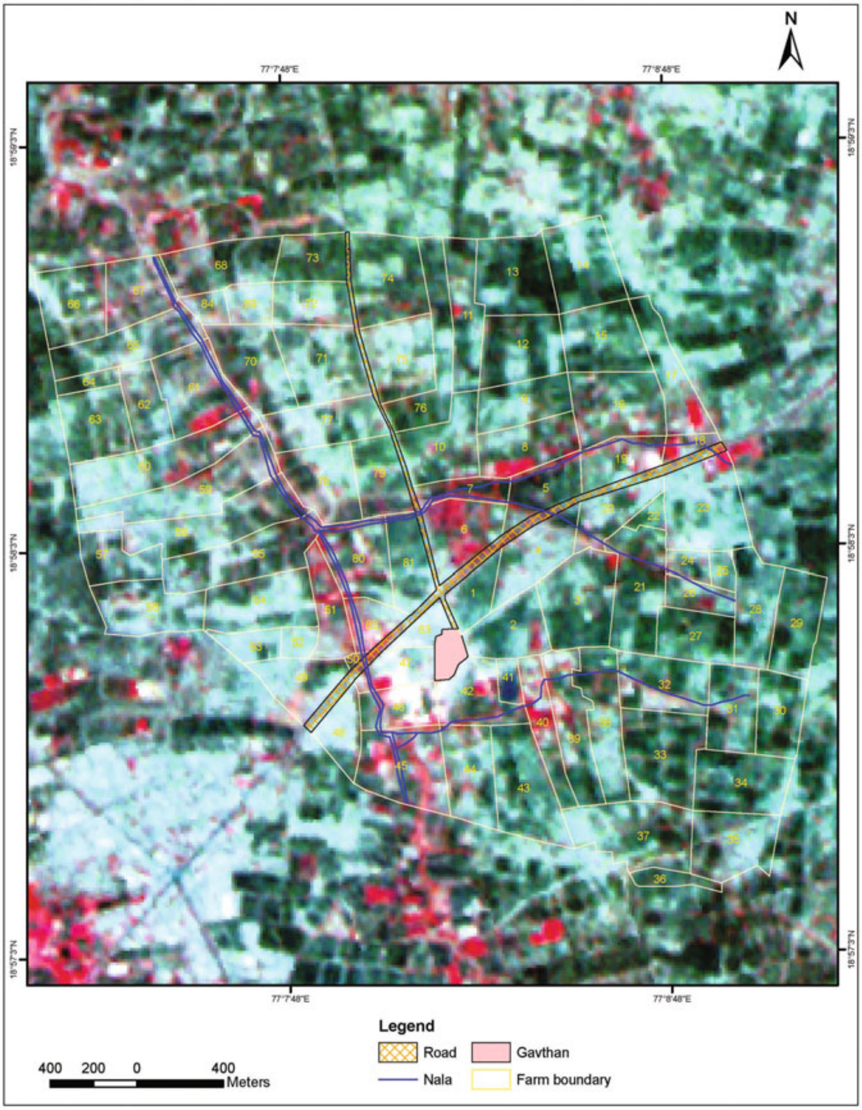


Fig. 6.35: Cadastral boundary of Pardi village on IRS satellite image April 2006.

Source: Taluk Inspector of Land Record, Govt. of Maharasthtra
IRS-P6 LISS-3 image of April 11, 2006

growth are continuously monitored in understanding the plant-growth stress. Satellite spatial ground resolution upto 1 m (IKONOS) is available for precise status of the agriculture plots. With Google Earth 4.3 on the internet you can tour distant cities with Google StreetView, view photo-realistic 3D buildings, and even show the sunset around the world with the new sunlight feature.

The maps and the satellite images on the web can also be used as tutor in understanding the water stressed surface conditions at different season. The continuous information thus collected needs to be stored in spatial data base for any retrieval and updation as described in the next chapter.

References

Bartholic, J.F., Namken, K.N. and Wiegand, C.L. (1972). Aerial thermal scanner to determine temperature of soil and crops canopies differing in water stress. *Agronomy J.*, **6**, pp. 603-608.

Brown, K.W. (1974). Calculation of evapotranspiration from crop surface temperature. *Agricultural Meteorology*, **14,** pp. 199-209.

Carnahan, W.H. and Larson, R.C. (1990). An analysis of an urban heat sink. *Remote sensing of Environment*, **33**, pp. 65-71.

Crist, E.P. and Cicone, R.C. (1984). Application of the Tosseled Cap concept for simulated thematic mapper data. *Photogrammetric Engg. and Remote Sensing*, **50(3),** pp. 343-352.

Flasse, S. and Verstraete, M.M. (1994). Monitoring the environment with vegetation indices, comparison of NDVI and GEMI using AVHRR data over Africa. *In:* Vegetation, modeling and climate change effects (eds) Veroustraete F. and Ceulemans, R. SBC Academic Publishing, The Hague, pp. 107-135.

Goita, K. and Rayer, A. (1992). Land surface climatology and land cover change monitoring since 1973 over North Sahelian Zone (Ansongo Mali) using Landsat data. *GeoCarto International*, **1,** pp. 15-28.

Hall, F.G., Shimbakuro, Y.E. and Huemmrich, K.F. (1995). Remote sensing of forest biophysical structure using mixture decomposition and geometric reflectance models. *Ecological Applications*, **5(4)**, pp. 993-1013.

Hanson, R.L. (1991). Evapotranspiration and droughts. *In:* US Geol. Survey Water Supply Paper 2375, pp. 99-104.

Janiski, M.F. (1996). Estimation of subpixel vegetation density of natural regions using satellite imagery. IEEE, *Transactions of Geoscience and Remote Sensing*, **34(3)**, pp. 804-813.

Joshi, A.K. (1998). Filtering applications in Geosciences. *In:* Remote sensing in Geoscience (eds) Tripathi, N.K. and Bajpai, V.N. Anmol Publications, New Delhi, pp. 39-55.

Kant, Y. and Badarinath, K.V.S. (1998). Regional scale evapotranspiration estimation using satellite derived albedo and surface temperature. *J. Indian Society of Remote Sensing*, **26(3)**, pp. 129-134.

Klette, R. and Zamperoni, P. (1996). Hand book of image processing operators. John Wiley and Sons, Chicester, pp. 397.

Kogan, F.N. (1995). Droughts of late 1980's in the USA as derived from NOAA polar orbiting satellite data. *Bulletin of American Meteorological Society*, **76,** pp. 655-668.

Kogan, F.N. (1997). Global drought watch from space. *Bulletin of the American Meteorological Society*, **78,** pp. 621-636.

Liu, W.T. and Kogan, F.N. (1996). Monitoring regional drought using the Vegetation Condition Index. *International Journal of Remote Sensing*, **17,** pp. 2,761-2,782.

Monteith, J.L. and Unsworth, M.H. (1990). Principles of Environmental Physics, 2nd Edition. Edward Arnold, London.

Pinty, B. and Verstraete, M.M. (1992). GEMI: A non-linear index to monitor global vegetation from satellites. *Vegetation*, **101**, pp. 15-20.

Rosema, A., Verhoef, W., Noorbergen, H. and Borgesius, J.J. (1992). A new forest light interaction model in support of forest monitoring. *Remote Sensing of Environment*, **42**, pp. 23-41.

Robinove, C.J. and Chavez (1981). Arid land monitoring using AVHRR NDVI data, reduction of environmental and inter-annual variability. *International J. of Remote Sensing*, **18,** pp. 1059-1077.

Sabins, R.F. (1978). Remote sensing – Principles and Interpretation. WH Freeman and Co, San Francisco, 425 pp.

Siegal, B.S. and Gillespie (1980). Remote sensing in Geology. John Wiley and Sons, New York, 702 pp.

Tucker, C.J., Townshend, J.R.G. and Goff, T.E. (1985). African land-cover classification using satellite data. *Science*, **227**, pp. 369-375.

Tucker, C.J. and Sellers, P.J. (1986). Satellite remote sensing of primary production. *International J. Remote Sensing*, **7**, pp. 1395-1416.

Valor, E. and Caselles, V. (1996). Mapping land surface emissivity from NDVI. Application to European, African and South American areas. *Remote Sensing of Environment*, **57**, pp. 167-184.

Further Reading

Barett, E.C. and Curtis, L.F. (1982). Introduction to Environmental remote sensing. Chapman and Hall, London, 352 pp.

Bhattacharya, A., Reddy, C.S.S., Reddy, P.R., Rao, D.P. and Chandramouli, K. (1991). Monitoring of live volcanic activity in Barren island, South Andaman, using satellite data. *Interface*, **2(3)**, p. 2.

Billingsley, F.C. (1983). Data processing and preprocessing. *In:* Manual of Remote sensing (ed.) Simonett, D.S. American Society of Photogrammetry, Virginia, pp. 719-792.

Tucker, C.J. and Choudhary, B.J. (1987). Satellite remote sensing of drought conditions. *Remote Sensing of Environment*, **23**, pp. 243-251.

Venkataratnam, L., Rao, P.V.N., Srinivas, B.R.M., Ramana, K.V.R. and Dwivedi, R.S. (1993). Soil moisture estimation using ERS-1 Synthetic Aperture Radar data. Proceedings 2nd ERS-1 symposium: Space at the service of our environment, Hamburg, Germany. 11-15 October.

7

Spatial Data and Geographical Information System

Regional planning and drought preparedness require an array of disparate pieces of information that have to be analyzed, evaluated and incorporated in the planning process. As our understanding will be formed about the reported events, we need to analyze the total natural hazards anticipated for the region with reference to the existing and planned developments and also calculate alternatives of mitigation prior to evaluation of the impact of the alternatives based on the economic and financial feasibility method. Assessment of drought requires information on various aspects from different sources such as meteorological and telecommunication satellites and ground-based measurements on the land-use, soil moisture content, crop condition and natural vegetation over a large area in addition to spatial distribution of human habitat, instant resource availability for sharing, infra-structure facility etc. Parameters which are used in drought and mode of input are shown in Table 7.1. This chapter highlights the information types that are required in drought vulnerability analysis and its spatial analysis using GIS.

7.1 Geographic Information System

GIS is an organized collection of computer hardware, software, geographic data and designed to efficiently capture, store, update, manipulate, analyze and display all forms of geographically referenced information. The *Geographic* implies that locations (latitude and longitude) of the data items are known or can be calculated. The *Information* is in an organized manner to yield useful knowledge, often as maps and images, but also as statistical graphics, tables and various on-screen responses to inter-active queries. *System* is interrelated and links components with difference functions. The various components of GIS include the hardware, software, data, people and the

Table 7.1: Information requirement for drought assessment and source

Information	*Remote sensing*	*Ground measurement*	*Indices*
Temperature	♦	♣	**Meteorological indices:** Dryness Index, De Martonne's Index, Pluvothermic Quotient, Bhalmey and Mooley Index, Rainfall Anomaly Index, Mean Monthly Rainfall Deficit, Rainfall deciles, PDSI, Relative Drought Resistance
Rainfall – monthly and annual	♦	♣	
Evaporation		♣	
Humidity		♣	
Soil Moisture	♦	♣	Crop Moisture Index, Soil Moisture content
Vegetation Cover	♦		Vegetation Condition Index, NDVI, Soil Adjusted Vegetation Index, Stress related TM based vegetation indices, Stress degree days, Crop yield estimation, Water demand analysis
Crop area and Type	♦	♣	
River Flow	♦	♣	Low flow Analysis, Total surface water and groundwater availability
Surface water storage area/volume	♦	♣	
Aquifer type		♣	
Groundwater level		♣	
Population		♣	Food and water demand analysis
Population density		♣	
Human and Livestock population		♣	
Agriculture dependant people		♣	Purchase capacity and target relief
Gross Income		♣	
Food storage facility		♣	Relief/Mitigation camp selection, and functioning
Medical facility		♣	
Transportation network	♦		

Orbital satellite images and ground measurements can be used in the assessment of the drought, individually or synergistically.

method of application (Fig. 7.1). The computer system on which the GIS software run is termed as *hardware* that gets input through the scanner or a digitizer board. *Software* provides the functions and tools needed to store, analyze and display information. There are several commercial and educational

GIS software (Table 7.2) to carry out the spatial data analysis (MapInfo, ERDAS, Intergraph, IDRISI, GRAM, ArcInfo, GRASS, AutoCAD maps etc). The functional modules that are available in the said commercial software are shown in Fig. 7.2. GIS has the functional capabilities for data capture, input, manipulation, transformation, visualization, combination, query, analysis, modelling and output. The user controls the operations with a graphical user interface (command language) consisting of program statements that provide support for making decisions based on spatial data.

Table 7.2: Availability of GIS Software platforms and their format

Vector format name	*Software platform*	*Raster format name*	*Software platform*
Arc Export	ARC/INFO – ESRI	Arc Digitized Raster Graphics (ADRG)	Common remote sensing standard
ARC/INFO coverage		Band Interleaved by Line (BIL)	
AutoCAD drawing files (DWG)	AutoCAD – AutoDesk	Band Interleaved by Pixels (BIP)	
AutoDesk data Interchange file (DXF)	Many – AutoDesk	Band Sequential (BSQ)	
Digital Line Graphs (DLG)	Many – USGS	Digital Elevation Model (DEM)	Many USGS
HP Geographic Language (HPGL)	Many	PC Paintbrush Exchange (PCX)	PC Paint brush – Zsoft
MapInfo data transfer file (MIF/MID)	MapInfo	Spatial Data Transfer Standard (SDTS)	Many
MapInfo Map files	MapInfo	Tagged Image file format (TIFF)	Page maker Aldus
Microstation Design Files (DGN)	Microstation-Bentley Systems		Internal
Spatial Data Transfer System (SDTS)	Many/US standard		
Topologically Integrated Geographic Encoding and Referencing (TIGER)	Many – US Census Bureau		
Vector Product (VPF)	US Defense Mapping Agency		

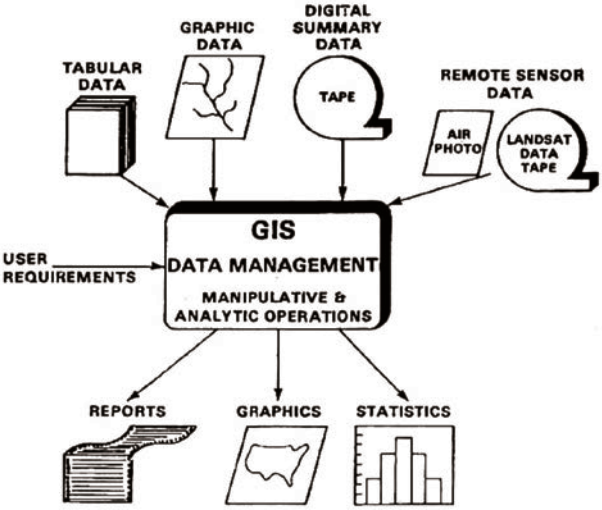


Fig. 7.1: Schematic diagram showing a generalized Geographic Information System.

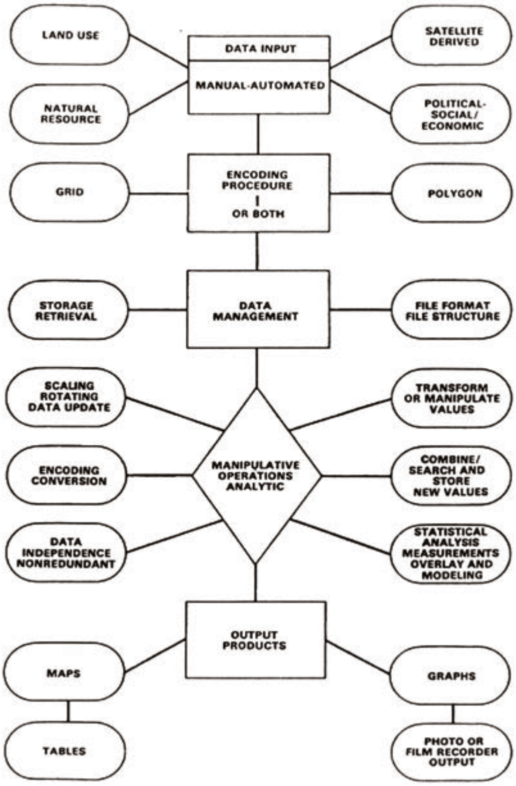


Fig. 7.2: Functional modules in GIS commercial software.

7.2 Spatial Data

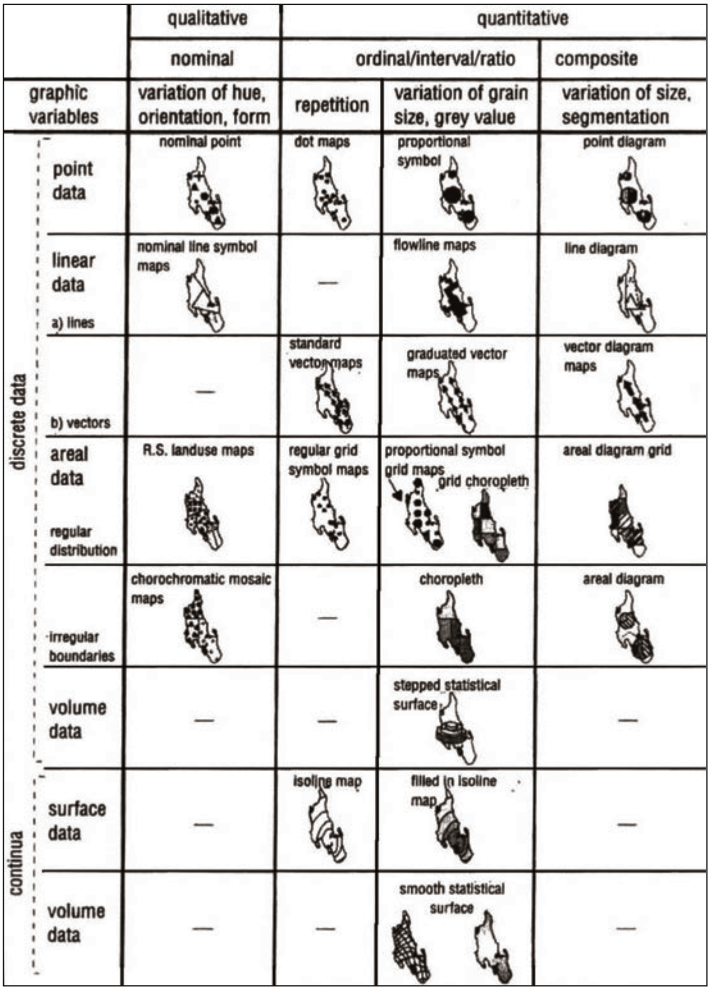
Spatial data from the paper maps, remote sensors and records need to be transformed into a digital format and create a spatial database. Keyboard digitizers, scanners, CCTS and interactive terminals or visual display units (VDU) are commonly used in the data input. Geographic references (longitude or latitude/columns and rows – spatial data) identify the spatial location of information collection. The attribute (non-spatial) data associate a numerical code to each cell or set of coordinates and for each variable, either to represent actual values (e.g. 700 mm precipitation or 1250 m elevation etc.) or to connote categorical data types (land uses, crop type). *Data storage* refers to the way in which spatial data are structured and organized within the GIS according to their location, interrelationship and attribute design. *Data manipulation and processing* are performed to obtain useful information from the data previously entered into the system. Manipulation embraces two types of operations: (1) operations needed to remove errors and update current data sets (editing) and (2) operations using analytical techniques – overlay of two or more maps or complex extraction of disparate pieces of information from a wide variety of sources. *Data output* refers to the display or presentation of data employing commonly used output formats such as maps, graphs, reports, tables and charts either as hard-copy, image on the screen or text file that can be carried away for decision making/used in early warning system/preparedness.

Spatial Data Type

A major portion of the effort in a GIS project is tied up in assembling the data in digital form and creating a geo-referenced spatial database in which all the maps, images and spatial data tables are properly geo-coded and in spatial register. Data sources are primary and secondary in nature. The *primary data* are usually observations taken at a point, either using in-situ measurements or laboratory measurements on samples. Geographic locations of these points are derived from topographic maps or Global Positioning Systems. Further the conversion of CAD drawings to topologically complete files can usually be carried out within a GIS. *Secondary data* is the interpreted, edited and processed information from the primary data. A GIS derived map layer might have undergone a straightforward transformation like a reclassification or it may have modified from the original source by a series of transformation and data combinations. The subsequent use of derived data sets prior to manipulation by others is dependent on the availability of informative records. It is referred as *metadata*. Planar map projection are being used for storing spatial coordinates in order to avoid the repeated transformation from geographic to projection coordinates every time the data are reviewed.

7.3 Thematic Map

Maps are uniquely powerful tools, and reveal spatial relations and patterns and offer an insight into distribution of particular phenomenon. Figure 7.3 shows the overview of some of the thematic maps illustrating the qualitative and quantitative information content (Kraak et al., 1996). An understanding of various aspects of the maps and the location-based information collection represented as a point in space prior to digital mapping is warranted.



		qualitative	quantitative		
		nominal	ordinal/interval/ratio		composite
	graphic variables	variation of hue, orientation, form	repetition	variation of grain size, grey value	variation of size, segmentation
discrete data	point data	nominal point	dot maps	proportional symbol	point diagram
	linear data a) lines	nominal line symbol maps	—	flowline maps	line diagram
	b) vectors	—	standard vector maps	graduated vector maps	vector diagram maps
	areal data regular distribution	R.S. landuse maps	regular grid symbol maps	proportional symbol grid maps grid choropleth	areal diagram grid
	irregular boundaries	chorochromatic mosaic maps	—	choropleth	areal diagram
	volume data	—	—	stepped statistical surface	—
continua	surface data	—	isoline map	filled in isoline map	—
	volume data	—	—	smooth statistical surface	—

Fig. 7.3: Overview of thematic maps and their qualitative and quantitative information.

Map Characteristics

Map resolution refers to how accurately the location and shape of map features can be shown in a map scale. In *larger-scale map*, the resolution of features matches with the ground reality. *Map accuracy* is measured by: absolute accuracy (relationship between a geographic position on a map and its real-world position), relative accuracy (displacement between two points on a map and the same points on ground), attribute's accuracy (precision of the attribute database linked to map features), map currency (revision date) and completeness (percent completeness). If the data is accurate, the decision making will be effective. The error accumulation is the product of various data input and the method by which it is collected.

$$\mathrm{E} = \mathrm{f}(f) + \mathrm{f}(l) + \mathrm{f}(e) + \mathrm{f}(d) + \mathrm{f}(a) + \mathrm{f}(m) + \mathrm{f}(\mathrm{rms}) + \mathrm{f}(\mathrm{mp}) + u$$

where f is transformation from spherical to planar geometry, l = accuracy of map projection and datum information, c = cartographic interpretation, d = drafting error (tracing of features), a = analog to digital conversion, m = media stability (warping and stretching, folding, wrinkling of map), p = digitizing processor error (cursor placement), rms = root mean square (registration accuracy of ties), mp = machine precision (coordinate rounding by computer in storing and transforming), and u is unexplained source error.

Map Projections

Transforming three-dimensional space onto a two-dimensional map is called projection. This process of inevitability distorts the shape, area, distance and direction. A systematic drawing of parallels of latitude and meridians of longitudes on a plane surface for the whole earth or a part of it on a certain scale defines it so that any point on the earth surface may correspond to that on the drawing. There are unlimited number of map projections available. They are based on the method of construction (perspective and non-perspective), preserved qualities (homolographic/equal area and orthomorphic/conformal), developable surface area (cylindrical, conical, azimuth/zenithal, conventional), position of tangent surface (polar, equation/normal, oblique), and position of viewpoint (genomic, stereographic, orthographic etc.). These projects represent an arrangement of lines of latitude and longitude in conformity with some principles so as to minimize the amount of distortion. Figure 7.4 shows the conical and cylindrical map projections.

The *cylindrical projection* is attained when a cylinder is wrapped round the globe so as to touch it along the equator and the light is placed at the centre. The exaggeration of the parallel scale as well as the meridian scale would vary greatly increasing away from the equator. *Equidistant cylindrical projection* represents a series of equal squares. All the parallels are equal to

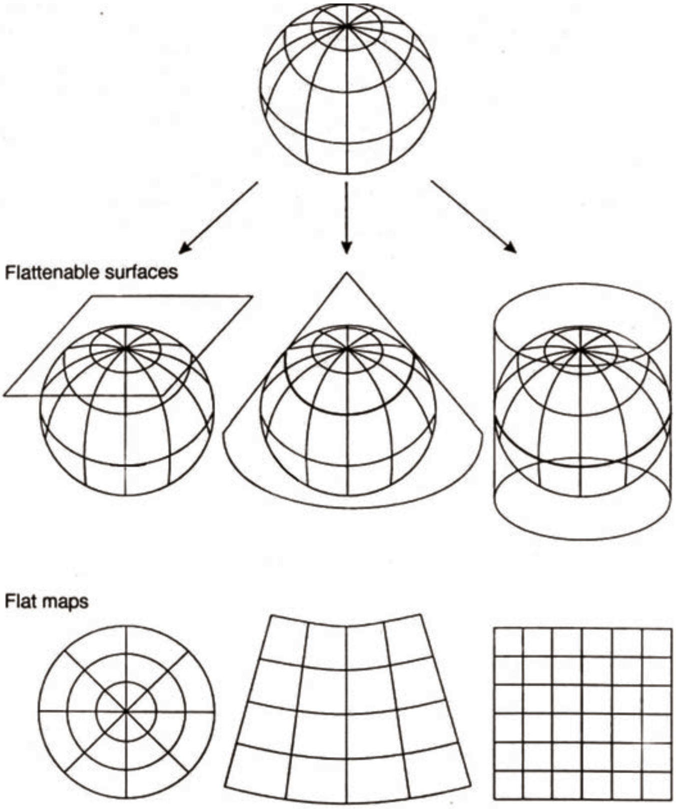
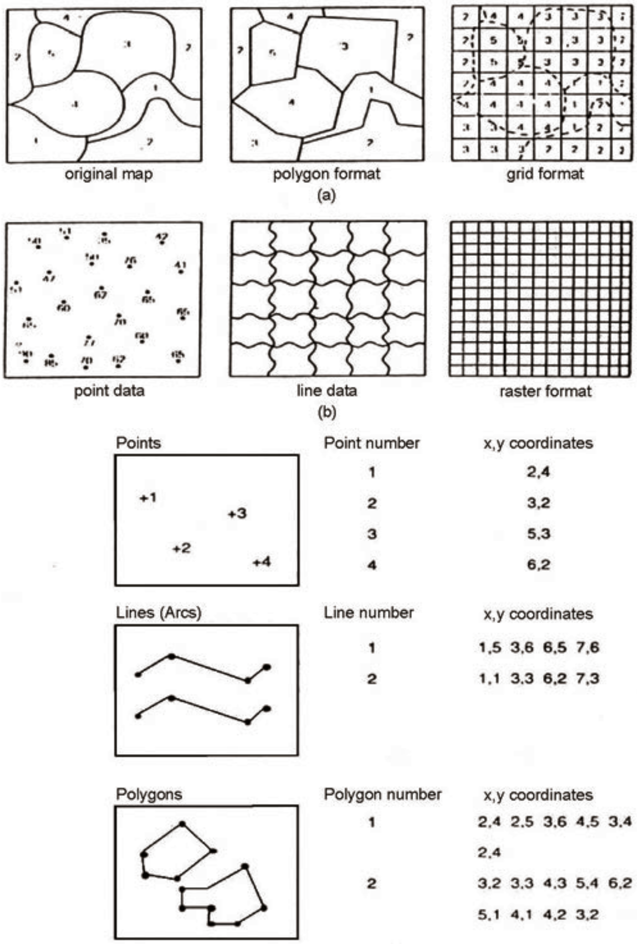


Fig. 7.4: Map projections that are used in the spatial data analysis.

the equator and the entire meridian is half of the equator in length. The projection is neither equal nor ortho-morphic. The scale along the equator is true but leads to greater distortion in shape and exaggeration of area in high latitudes. In the *cylindrical equal area projection* by Lambert, the area between two parallels is made equal to the corresponding surface on the earth, at the cost of great distortion in shape towards higher latitudes. In *conical projection*, the surface of the cone will be tangent to the sphere along some parallel of latitude, also known as standard parallel. Conics are true along some parallel somewhere between the equator and the pole and the distortion increases away from this standard. It is good for temperate zones. Zenithal projection views the globe from a point vertically above it, hence known as azimuthal. It is true only at their central point, but generally distortion is worst at the edge of the map and good for polar areas. Polynomial, Mercator, Universal Transverse Meridian etc. are some of the projections that are commonly used in the map preparation.

Location Information

Location information of wells, village, sample locations, etc. is represented by points; streams, road, etc. by lines; and lakes, reservoir etc. by areas. *Point feature* represents a single location; they are zero-dimensional objects with only a position in space but no length. *Linear feature* by a set of connected ordered coordinates represent the linear shape of a map object that may be too narrow to display as an area. It is also termed as segments or arcs which are one-dimensional spatial objects having a position in space and length. *Area feature* is a closed feature whose boundary encloses a homogeneous area. They are termed as polygons and are two-dimensional spatial objects (Fig. 7.5). They have position in space and length and also width. Continuous surfaces are three-dimensional spatial objects with a position in space, length and width in addition to depth or height.



Point number	x,y coordinates
1	2,4
2	3,2
3	5,3
4	6,2

Line number	x,y coordinates
1	1,5 3,6 6,5 7,6
2	1,1 3,3 6,2 7,3

Polygon number	x,y coordinates
1	2,4 2,5 3,6 4,5 3,4 2,4
2	3,2 3,3 4,3 5,4 6,2 5,1 4,1 4,2 3,2

Fig. 7.5: Representation of point, line and area on digital data base.

7.4 Data Conversion

Manual digitizing or raster scanner by optical scanner is used in the digital capturing of data from maps. Manual digitizing uses a digitizing table which is like a drafting table with a stylus or cursor for tracing and electronically recording the positions of points and lines (Fig. 7.6). The electronics in the system convert the position of the cursor to a digital signal with a precision of about 5 to 50 points per mm and area transmitted to the computer for storage. The resulting strings of spatial coordinates comprise the raw data for the vector representation of points, lines and polygons. The accuracy is improved by number of control points and by skill of the operator. Improper line-node joins cause the errors that require editing. *Optical scanners*, such as rotating drum or flatbed variety, are used in raster scanning (Fig. 7.7). It generates a large matrix of digital values, each pixel integrating the reflectance over a small portion of the original image. The radiometric resolution (600 to 200 dots per inch (dpi)) describes the range of values the device can discriminate per pixel. It varies broadly and the drum scanner can accommodate documents unto 1 m. Images scanned from maps are sometimes used as backdrops on which other data are displayed without attempts to extract points, line and polygon objects or to eliminate superfluous symbology. Raster image that is displayed on the screen and a cursor controlled by a trackball is moved onto one of the lines to be captured. The line is then followed automatically until operator-intervention becomes necessary. The

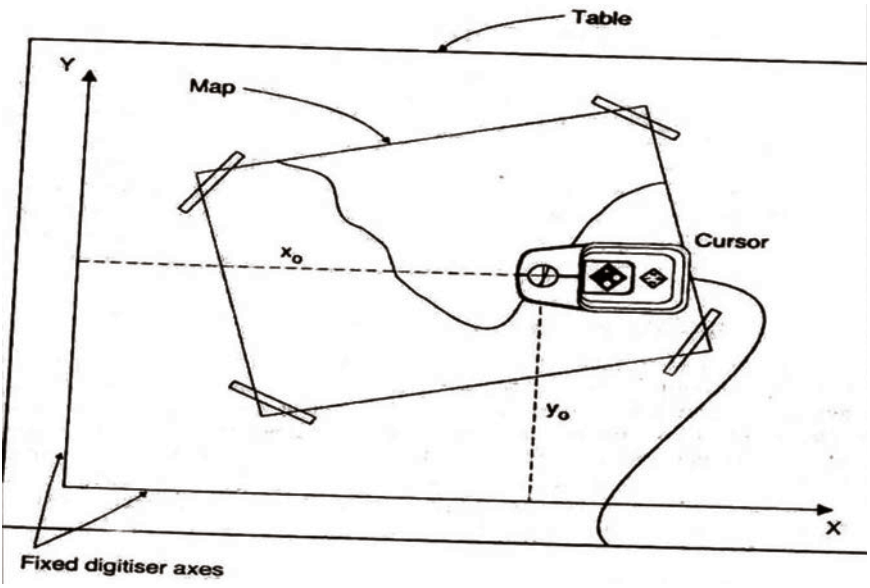


Fig. 7.6: Manual digitization.

lines are automatically digitized during tracking and producing vector data. The resulting file is then an edited topology thus built and polygons are tagged. Thus the minimum operator control reduces manual editing. The various errors that are encountered in the digitization are given in Fig. 7.8. A combination of scanning and on-screen manual digitizing of the scanned document is now called heads-up digitizing.

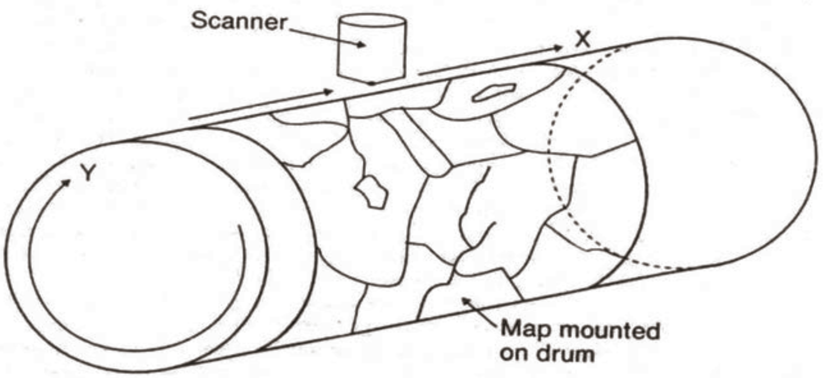


Fig. 7.7: Optical scanner and digitization of maps.

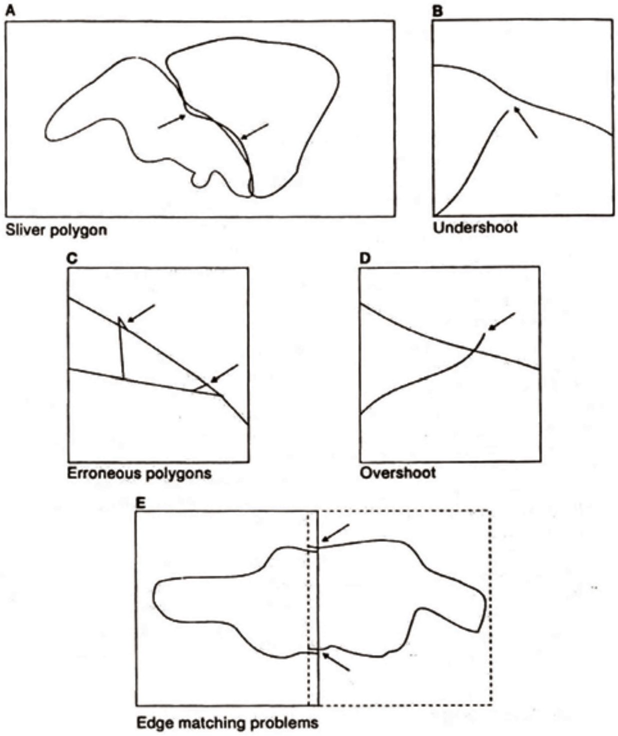


Fig. 7.8: Digitization errors that are encountered.

Presentation of Information

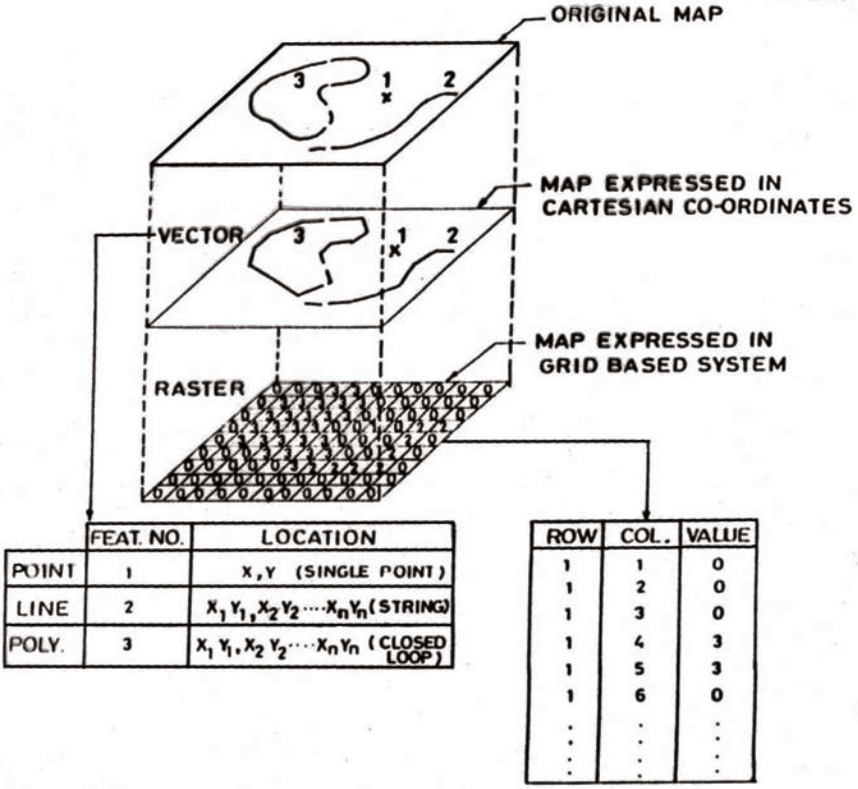
Attribute information – It describes the specific map features for vector maps. It is often stored in a data base file kept separately from the graphic portion of the map. Software package maintains an internal link between the map graphic entity and its attributes. Links in these systems take the form of database keys. Each map feature has a key value stored with it; the key identifies the specific data base record that contains the feature attribute information. *Display information* – It describes about how the map is to be displayed or plotted. It includes feature colours, line widths and line types (solid, dashed, dotted, single or double etc.), how the names of the roads and other features are shown on the map; and whether or not lakes, parks or other area features attribute information. The users do not give importance to the quality of display information when they evaluate the data set. *Cartographic presentation* determines the effectiveness of the output. Appropriate colour choices, line types etc. will enhance the product. The following aspects would improve the cartographic presentation: feature colour and line types, naming of roads, landmark symbols, polygon fills, zoom layer control etc.

7.5 Data Models

Data modelling is the process of defining and organizing data about the real world into a consistent digital data set and that is useful and reveals information. A data structure must be chosen to represent the data model and finally a file format must be selected that is suitable for that data structure.

Vector and Raster Model

All spatial data models make use of discrete spatial data objects such as points, lines, areas, volumes and surfaces. Attributes that are both spatial and non-spatial and the digital description of objects characterize them and their attributes comprise spatial data sets. Vector and raster models are commonly used in data organization (Fig. 7.9). The line work is represented by a set of straight-line segments called vector. The X, Y co-ordinates at the end of each vector segment are digitized and explicitly stored and the connections are implied through the organization of the points in the database. A raster/cell-based model represents a map by a geometric array of rectangular or square cells each with an assigned value. The *vector model* divides the world into points, lines and areas bounded by lines whereas the raster model uses cells or pixels as spatial units. A database is a collection of inter-related data and everything that is needed to maintain and use it and database management system is a collection of software for storing, editing and retrieving data in a database. Spatial and non-spatial data are managed separately in GIS. Natural spatial objects correspond to discrete spatial entities recognizable in the real world, like a river or a mountain. Imposed spatial objects are manmade or artificial entities like a property or pixel.



	FEAT. NO.	LOCATION
POINT	1	X, Y (SINGLE POINT)
LINE	2	$X_1 Y_1, X_2 Y_2 \cdots X_n Y_n$ (STRING)
POLY.	3	$X_1 Y_1, X_2 Y_2 \cdots X_n Y_n$ (CLOSED LOOP)

ROW	COL.	VALUE
1	1	0
1	2	0
1	3	0
1	4	3
1	5	3
1	6	0
.	.	.
.	.	.
.	.	.
.	.	.

Fig. 7.9: Vector and caster models.

The advantages of the *raster model* is that spatial data of different types can be overlaid without the need for the complex geometric calculations required for overlaying different maps in the vector model. Each layer of a grid cell in a raster model records a separate attribute. Row and column number and the geological location of the origin of the rows address the cell locations and columns are saved with each layer. Spatial resolution of a raster is the size of one of the pixels on the grounds. A 100 m resolution, a square area 100 km on a side requires raster with 1000 rows by 1000 columns. The points are represented by single pixels and lines by strings of connected pixels. Processing raster data is efficient in neighbourhood query operations such as filtering that carry out calculations on a square window of adjacent pixels and overlay operations for combining two or more images together. It is best suited for modelling spatial continua, particularly where an attribute shows a high degree of spatial variation (satellite images).

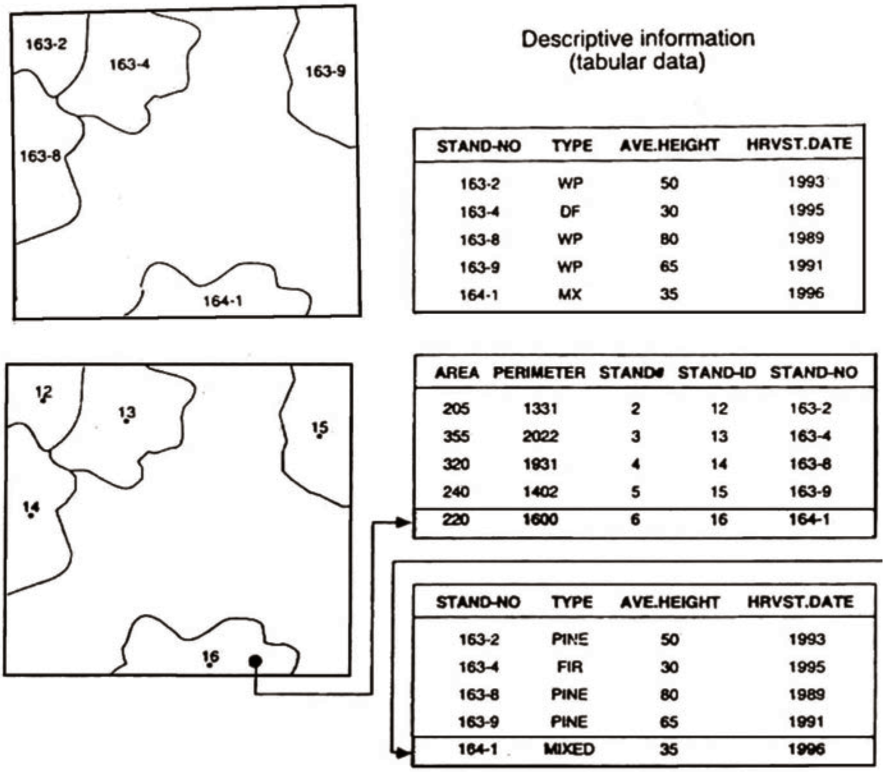
Spaghetti Model

The points are represented as pairs of spatial coordinates, lines as strings of coordinate pairs and areas as lines that form closed loops or polygons. This straightforward model and the equivalent data structure are ideal for inexpensive graphical systems. Digital drawings can be readily scaled, transformed to various projections and output to pen-plotters or displayed on a video-screen. The attribute information can usually be plotted with different symbols, lines and colour depending on the values associated with it. Computer-Aided Drawing (CAD) package offers impressive functionality in digitization maps and display.

The spatial relationship between connecting or adjacent coverage features (e.g. arc, nodes, polygons and points) is termed as topology. It is built from simple elements into complex elements – points (simplest element), arcs (sets of connected points), areas (sets of connected arcs) and routes (sets of sections which are arcs or portions of arcs). Redundant data (coordinates) are eliminated because an arc represents linear features, part of the boundary of an area features or both. In topological model, the boundaries of polygons are broken down into series of arcs and nodes, and the spatial relationship between arcs, nodes and polygons are explicitly defined in attribute table. Topological attributes of spatial objects are those spatial characteristics that are unchanged by transformations such as translation, scaling, rotation and shear. Spatial co-ordinates and geometric attributes are affected by changes, but contiguity (pertaining to spatial adjacency) remains the same. This model results in efficient computer processing, where topological information is required.

Geo-relational Model

In Geo-relational data model, the files are geo-referenced which refer to the location of a layer or coverage in space defined by the coordinate reference system. It abstracts the geographic information into a series of independent layers or coverage; each representing a selected set of closely associated geographic features. Each layer has the theme of the geographic feature and the database organized in the thematic layers. *Topological data structure* – Topology is the spatial relationship between connecting and adjacent coverage features (arc, polygons and points). Its relationships are built from simple elements into complex elements: point, arc and areas (Fig. 7.10). *Attribute data management* – It is a two-dimensional structure that contains data and it corresponds to a table. A row of the relation is a tuple and column is a field or attribute. The tuple is analogous to data record in a flat file and contains collection of data items that describe an object or entity. A key or key field is an attribute that uniquely identifies tuples and provides a link between one relation and another.



STAND-NO	TYPE	AVE.HEIGHT	HRVST.DATE
163-2	WP	50	1993
163-4	DF	30	1995
163-8	WP	80	1989
163-9	WP	65	1991
164-1	MX	35	1996

AREA	PERIMETER	STAND#	STAND-ID	STAND-NO
205	1331	2	12	163-2
355	2022	3	13	163-4
320	1931	4	14	163-8
240	1402	5	15	163-9
220	1600	6	16	164-1

STAND-NO	TYPE	AVE.HEIGHT	HRVST.DATE
163-2	PINE	50	1993
163-4	FIR	30	1995
163-8	PINE	80	1989
163-9	PINE	65	1991
164-1	MIXED	35	1996

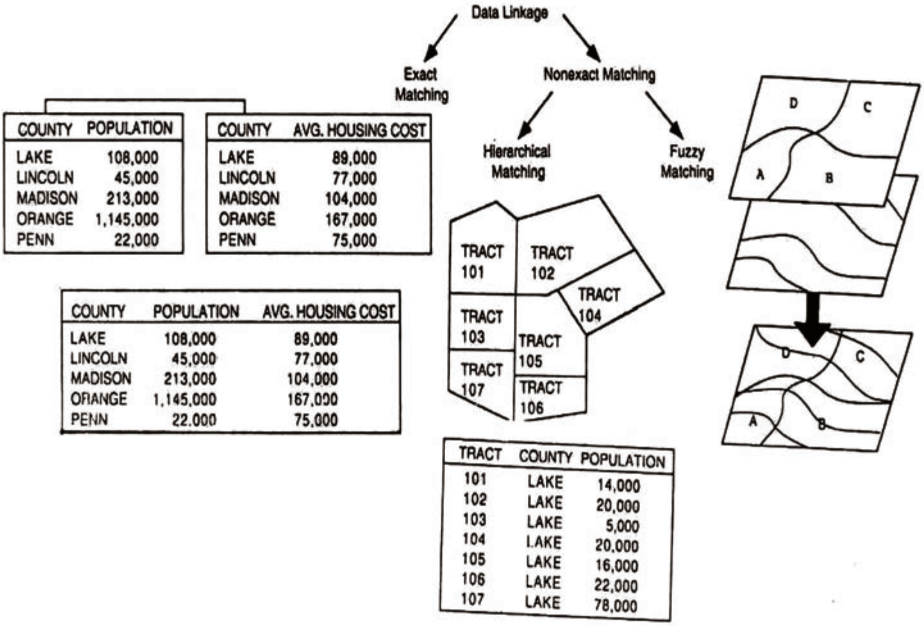
Fig. 7.10: Topological presentation of polygon-arc and arc-node.

7.6 Attributes of Data

Spatial, temporal and thematic attributes of objects are to be recorded in a database. They are lumped together as being non-spatial and are based on primary observations or arrived from secondary processing calculation or processing. *Spatial attributes* record data about the location, topology and geometry of the spatial objects. Spatial location about an object is recorded either in latitude/longitude coordinates or one of the standard cartographic projects or in arbitrary rectilinear coordinates with a local origin. Non-spatial attributes such as temporal and thematic attributes are treated similarly in GIS. Temporal attributes refer either to age of the objects or to the time of data collection or measurement. Thematic attributes refer to other kinds of properties of objects that are neither location-based nor temporal, such as rock type, annual rainfall, the presence of minerals and fossils etc. Measurement attribute is made according to various scales of or levels of measurements. Attributes of spatial objects are usually organized into lists or tables as that of flat files, two-dimensional arrays of numbers with rows being the entities or objects and columns being the attributes. Database systems are based on either the hierarchical, network or relational models but in recent years the relational model has become the most widely used. The geographical data and the attribute information should match each other. *Exact matching* occurs when the geographical information is file one and the additional attribute information is in another file, located in the same system, but identified by a key (Fig. 7.11). They can be joined and stored in another file. *Hierarchical matching* – If the information content for an area differs from a unit to another unit, due to various reasons of data collection, the smaller and information groups are arranged in a hierarchical manner. It is identified by a tract designation. *Fuzzy matching* – If the boundaries of smaller areas do not match those of the larger ones, geographic location used as common identification is matching the data.

Triangulated Irregular Networks (TIN)

Triangulated Irregular Network (TIN) is used to subdivide the surfaces into triangular facets and Thiessen polygons. They are used to partition space



COUNTY	POPULATION
LAKE	108,000
LINCOLN	45,000
MADISON	213,000
ORANGE	1,145,000
PENN	22,000

COUNTY	AVG. HOUSING COST
LAKE	89,000
LINCOLN	77,000
MADISON	104,000
ORANGE	167,000
PENN	75,000

COUNTY	POPULATION	AVG. HOUSING COST
LAKE	108,000	89,000
LINCOLN	45,000	77,000
MADISON	213,000	104,000
ORANGE	1,145,000	167,000
PENN	22,000	75,000

TRACT	COUNTY	POPULATION
101	LAKE	14,000
102	LAKE	20,000
103	LAKE	5,000
104	LAKE	20,000
105	LAKE	16,000
106	LAKE	22,000
107	LAKE	78,000

Fig. 7.11: Description, graphic and tabular data – data linkage.

into a specialized type of mosaic that fall into this category. Representation of sample locations, roads etc. can be input like this. Any regular subdivision of space produces regularly shaped area objects; such square pixels in raster image or raster-based on hexagons or equilateral triangles are known as regular imposed spatial objects. TIN is used to represent digital elevation surfaces. The *Vornoi model* subdivides a region of Thiessen or Voronoi polygons. The polygons have the property that the sides are always at right angles to a line joining adjacent points and that any location within a polygon is closer to the point in that polygon than to the point of neighbouring polygon. The data is derived from attributes and the surface to be modelled is the height of an attribute measured at a point. This model converts the point objects into a mosaic of area objects that approximate a surface. The resulting surface is usually treated as a vector representation. It is advantageous for allowing discontinuities such as cliffs, faults, coastlines and valley bottoms to be explicitly modelled using breadlines (McCullagh, 1988). Thiessen models consist of a mosaic of polygons; one polygon per data point.

7.7 Spatial Data Transformation

GIS facilitates the transformation from one coordinate set to another for better perspective and display. This is achieved by data interpolation, contouring and creation of Thiessen polygons from points, lines into line intersections, line smoothing and creation of buffer zones and areas into sample at points, medial axis and re-sampling. *Point to area conversion* is essential as most of the ground-based measurements represent the site conditions. Attribute information measured at points are converted into attributes of area objects. The resultant map layer either in raster or vector mode could be visualized, analyzed and modelled as a semi-continuous or discontinuous piecewise surface, depending on the measurement scale of the attribute. Surface modelling of spatially continuous field variables involves interpolation from the irregularly spaced samples to a grid of points that is normally treated as a raster. Alternatively triangles are used to link the points using the TIN model and the surface is treated as a mosaic of triangular planar facets (Fig. 7.12). *Density Mapping* creates a digital model of a surface but the height of the surface is not the value of a thematic point attribute but is the point density or number of points per unit area. It is practiced over a raster image or irregular polygons in a vector model. A simple method of generating a surface is by superimposing a grid and counting the number of points per cell. The resulting surface tends to be blocky unless the number of points per cell is large. A smoother surface is achieved by using a moving window method (normally either a circular or rectangular window), counting the number of points in a window and moving the window progressively over the map on a lattice to produce a raster.

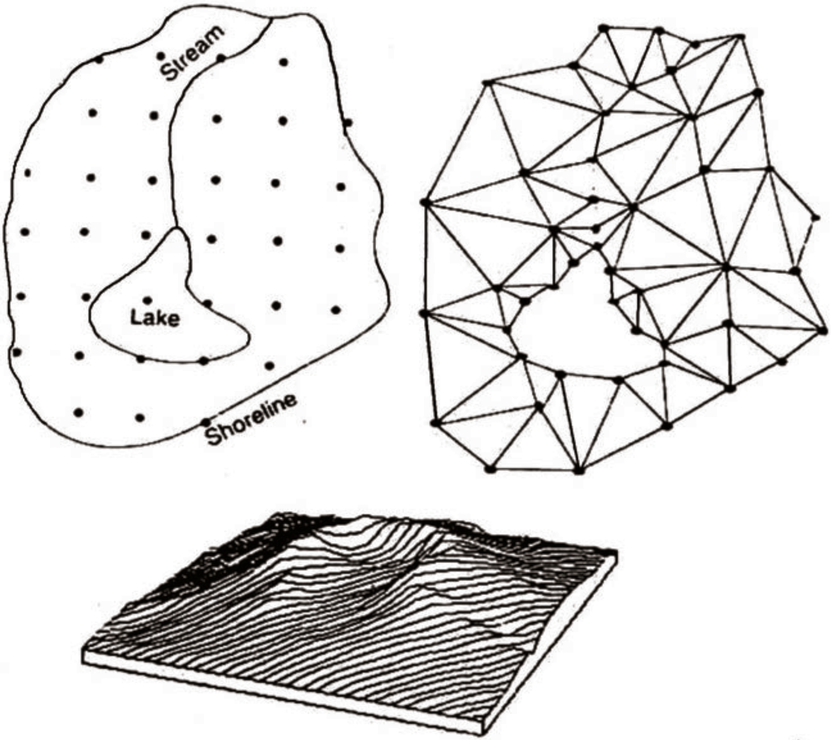


Fig. 7.12: TIN model.

Conversion of Points

Point samples are converted into areas that can be subdivided into two groups depending whether or not spatial interpolation is involved. Non-interpolation method involves the assignment (Fig. 7.13) of one or more attributes of a point to a polygon. The polygon represents the points and becomes the spatial object with which one or more attributes are associated. *Method 1:* Each point is associated with a cell of a grid. Cells that contain no points are given null attributes and the attributes of cells that contain more than one point are determined by aggregating attributes according to some rules such as assigning the mean, median, mode, maximum or minimum depending on the scale of measurement. This method is effective for a small-scale mapping using the median as an aggregation. *Method 2:* Assign the points and their attributes to circular polygons each circle centered on a point. Regions not covered by a circle are assigned null attributes. The satisfactory performance is achieved where points are not clustered. The advantage of this method is the size of the zone of influence of points. *Method 3:* This method overcomes the problem of polygons either having no points or more than one is to generate Thiessen (also known as Voronoi) polygons. Even though the Thiessen polygon contains a single point, it has useful property that any location within a polygon is closer to the associated point than to any of the neighbouring points. Thiessen polygons also have the property that the line linking a pair of neighbouring points is bisected at angles by the intervening polygon boundary.

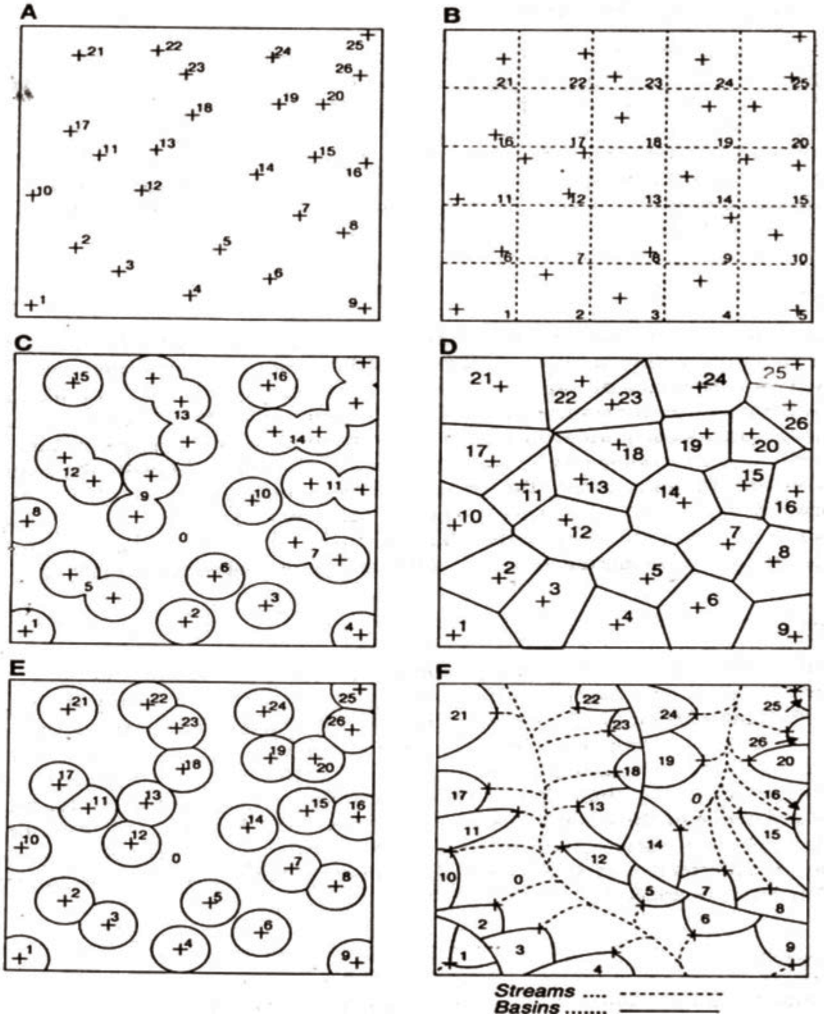


Fig. 7.13: Spatial data conversion.

Interpolation Method

When an attribute is measured at sample point, it is spatially continuous and a single-valued surface. Interpolation methods are effective for converting points to an area representation. The interpolation process involves estimating the value of the modelled variable at a succession of point locations, usually on a square lattice and is called Griding. The gridded values are treated as the pixels of a raster image. These grid values are used in contour lining or surface modelling or as labelled line objects or polygon objects whose boundaries are the contours. The process of converting point data to data structure that represents a continuous surface is called contouring or surface modelling. Surface modelling is achieved through triangulation, distance weighing and Kriging.

Triangulation Method

In this method sample lines to form a mosaic of triangles join points. Adelaunay triangulation method produces triangles that are as close to being equilateral as possible. Each triangle is treated as a plane surface. One of the advantages of this method is that breaklines can be readily inserted on the surface where discontinuities occur. Special calculations are used at triangles adjacent to breaklines to ensure discontinuity that yields surface configurations to satisfy the continuity conditions elsewhere.

Inverse Distance Weighing

It is one of the simplest methods of weights that are inversely proportional to the square of the distance from the centre of the zone of influence. The formula for inverse distance weighing (IDW) is:

$$Z_o = \Sigma_{I=1}\ w_i Z_i /^n \Sigma_{I=1}\ w_i$$

where Z indicates an estimated value of surface height. The subscript 0 refers to the estimation point and the subscript I refers to the sample points falling within the zone of influence. The advantage of the methods is that points within the inner circle can be assigned an equal weight, which may be desirable in some circumstances. It does not produce a surface that does not honour the data point. The major disadvantage of this method arises from the arbitrary choice of parameters for the weighing functions.

Dialation of Spatial Objects

It creates a map that shows proximity to selected features. Map showing proximity to roads or railways can be used as components of multimap GIS analysis. Dialation operation in mathematical morphology is part of a family of transformations that extend the notion of buffering to allow more complex changes in an image. The objects can be made smaller by dialation or subjected to opening and closing transformation. Dialating linear features are used to measure distance distribution of and number of villages from the main, etc. Mathematical morphology of dialation could be seen from Fabbri (1984). Besides re-sampling images for geometric correction, sampling of lines is also widely used for the purpose of data compression. Lines digitized in a stream mode can be weeded to reduce the number of vertices. Douglas-Peucker algorithm (Cromley, 1992) is widely used for this purpose.

7.8 Data Analysis

The significant use of GIS is its ability to combine spatial data from different sources together to identify and describe spatial associations present in the data and use models for analysis and prediction of phenomena such as drought. This could be achieved by way of database query, overlay, proximity analysis, network analysis, digital terrain model and statistical and tabular analysis.

Database Query

The ability to selectively retrieve information from GIS is an important facility by way of query related to attribute or geometry. Standard Query Language (SQL), a function of RDBMS, is used in retrieving map features on the basis of attributes that is stored in table (relational database mode) with a unique code linked to geometric data. It helps in checking quality of data and the results obtained. Interactive queries allow the user to obtain answer by a click. Vector GIS queries allow for complex queries such as the shortest distance between X and Y. Aspatial and spatial criteria can be included using Boolean operators.

Buffer Operation

It evaluates an area surrounding in a specified location. It is also known as proximity analysis that is used wherever there is a requirement for surrounding geographic features. The buffer operation will generate polygon feature types irrespective of geographic features and delineates spatial proximity. It requires the target locations, unit of measure, a function to calculate proximity and the area to be analyzed. This can be operated for a point, line or area data. Proximity calculated will result in a new raster data layer where the attribute of each cell is a measure of distance 250, 500 and 1000 m. Buffer distance from the lakes were created in understanding the fetching of water by the population in the settlement, as a drought minimizing method (Fig. 7.14).

Neighbourhood operation use a square or circle shape to filter; pass filter over raster data; recalculate value of each cell based on the neighbours; and use maximum or average or mode for calculation. The filtering reduces speckles and helps to smooth noisy data.

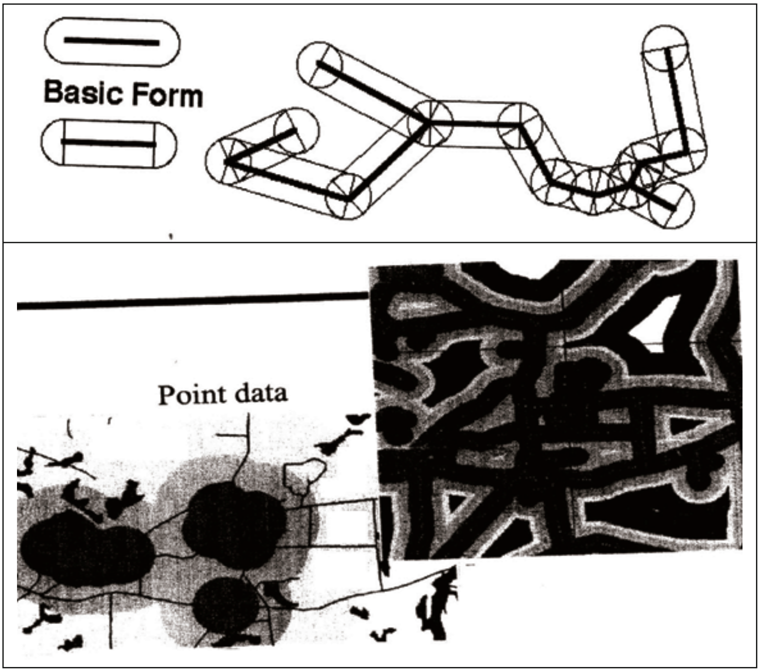
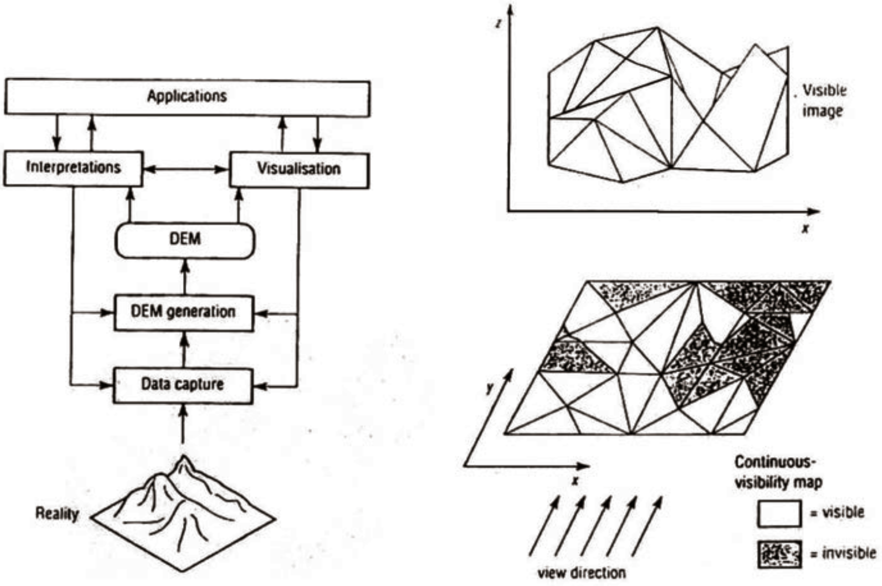


Fig. 7.14: Area of influence – buffer zone and proximity analysis.

Digital Terrain Model

Three-dimensional representations of terrain form natural backgrounds for the display of spatially distributed quantities and entities. The rationale for the digital terrain-modelling scheme is shown in Fig. 7.15. Elevation contours are the principal data source for interpolation of DEMs in addition to synthetic aperture radar and laser systems and Global Positioning System. The task involved in the DEM (Fig. 7.16) generation is editing, resampling and data structure conversion between regular grids and triangulated irregular networks (TIN). TIN is the most effective tool in visualization applications, while regular-grid DEMs for environmental monitoring and drought-related studies. DEM interpretation includes scale analyses, terrain parameters and terrain features. Scale and resolution are analogous to the map scale in cartography. Grid resolution is used as an index of information content. Terrain features are usually defined in terms of surface shape and drainage structures.



The main tasks associated with digital terrain modelling.

The continuous-visibility map and the visible image of a TIN. The viewpoint lies at infinity in the negative *y* direction, an the *x*, *z* plane is used as the viewplane.

Fig. 7.15: Schematic diagram showing the Digital Terrain Model.

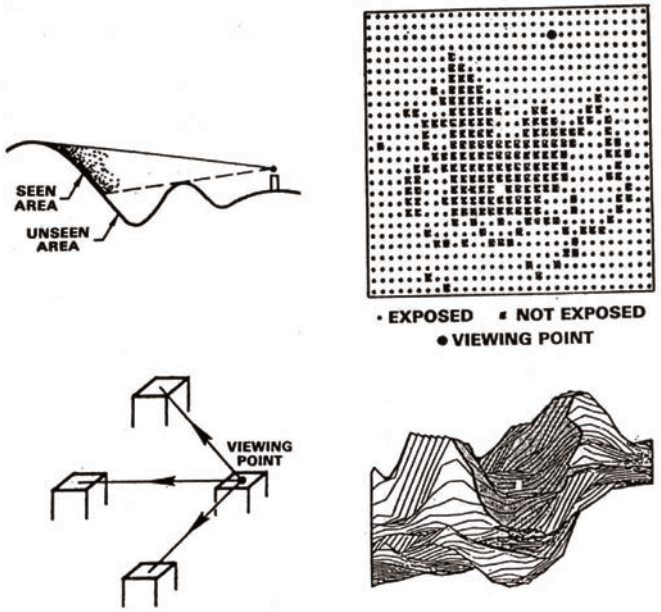


Fig. 7.16: DEM generation.

Visualization of DEMs draped with various textures can also provide valuable insight into the nature of processes being represented. Figures 7.17 and 7.18 show the perspective view of the terrains – Koyna (mesh type) and part of western ghat around Neduvayal in Kerala respectively.

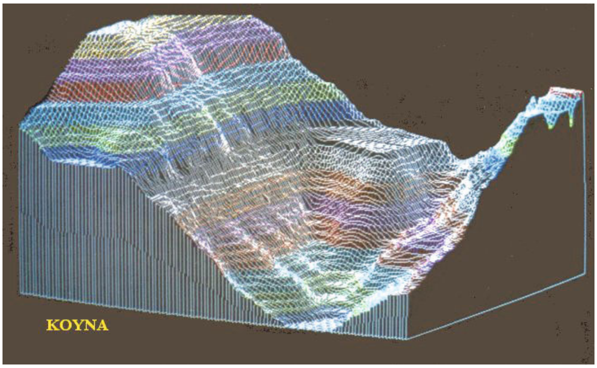


Fig. 7.17: Perspective view of Koyna valley – mesh type.

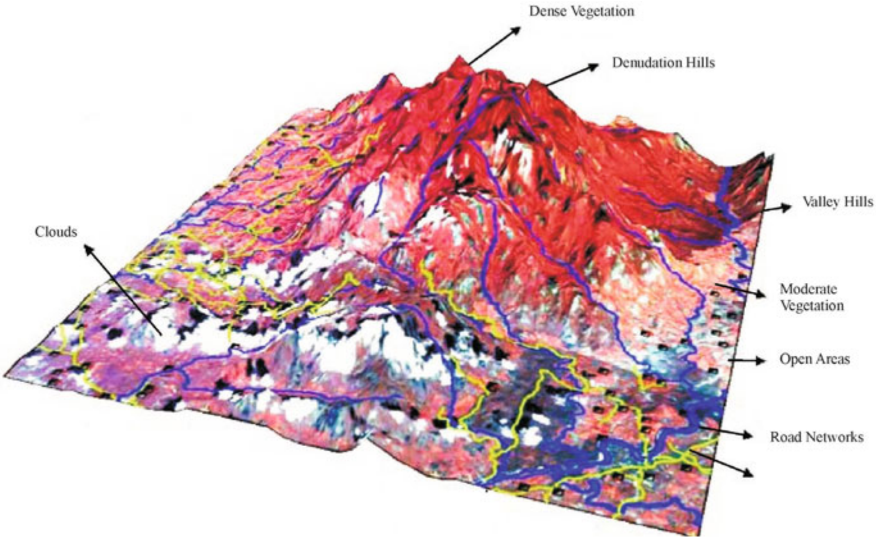


Fig. 7.18: Three dimensional visualization of hill slope surface cover – IRS FCC over DEM.

DEM Generation

Surface-specific point elevations, including high and low points, saddle points and points on streams and ridges, make up the skeletons of terrain. They are the ideal source for most interpolation techniques, including triangulation methods and girding method. Contour data is still the most common terrain data source. They are digitized from the topographic sheets. Contours implicitly encode a number of terrain features. The main disadvantage is that they significantly under-sample the areas between contour lines in areas of low relief. Gridded DEMs have also been calculated from stereoscopic interpretation of data from airborne and satellite sensors. Data from airborne SAR data can be as small as 1 to 3 metres.

Interpolation Methods

High quality global interpolation methods such as thin plate splines are needed to generate DEMs from surface-specific points and from contour and streamline data. Large volume of data sets, inverse distances weighing, local Kriging and unconstrained triangulation methods are commonly used. *Triangulation* is achieved by constructing a triangulation of the data points, which form the vertices of the triangles and then fitting local polynomial functions across each triangle. Linear interpolation is the simplest and Delaunay triangulation is the popular method. Local surface patches are achieved by applying a global interpolation method to overlapping regions, usually rectangular in shape and then smoothly blending the overlapping surfaces. Direct gridding or finite-difference methods can provide a computationally efficient means of applying high-quality interpolation methods to large data sets. Computing shaded relief allows a rapid visual inspection of the DEM for local anomalies that show up as bright or dark spots. It also indicates both random and systematic errors.

Specific manipulations of a topological nature such as *Slope analysis* is used to calculate by the steepest drop, steepest rise and drop, mean of absolute slopes and a variety of vector summations. Slope analysis is performed rapidly and consistently using elevation contour information derived from topographic sheets. *Aspect analysis* – It is a condensed way of saying directional orientation. It is used in related parameters such as temperature, humidity, wind etc. *Exposure* is also known as view-shed analysis or landform exposure. It determines a user-defined observation points in a study area from which any other specified point or area in a scene is open to view. The user has variety of options for specifying the observation points. The user has to choose the direction of orientation (north, south etc.) and the elevation associated with the point or area to be observed. *View* produces three-dimensional line drawing which displays topographical surface. The program decides which parts on the surface are hidden and which parts are viewable. It also produces a cross section or vertical slice through a topographical surface, provided that subsurface information is available. This program is effectively used for location analysis with respect to topographical relief, direction and elevation. *Topographical transformation* – Digital topographical data can be re-sampled to the pixel size of the satellite data. The information can be draped over it.

Network Analysis

It is based on interconnecting logical components such as nodes, chains and links. This could be used in the analysis of street and road network flow modelling, etc. It extracts data from network of information, processes it and derives new information.

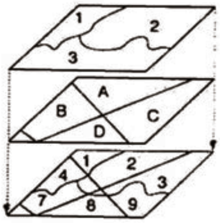
Overlay

Overlaying of maps creates new spatial elements. Raster to raster overlay is simple and the vector overlay is complex and involves more processing. Logical operators are Boolean functions. There are various types of Boolean operators: viz. OR, AND, NOT and XOR. In vector overlay, map features and associated attributes are integrated to produce new composite maps. Vector overlay is performed by way of (1) Polygon-on-polygon overlay, (2) Line-in-polygon overlay and (3) Point-on-polygon overlay (Fig. 7.19). The attribute data associated with each feature is merged. The resulting table will contain both attribute data. There is a need to carry out a series of overlay procedures to arrive at the conclusion. In raster overlay, the pixel or grid cell values in each are combined using arithmetic and Boolean operators to produce a new one in the composite map. The resulting map will be treated as arithmetical variable and perform complex algebraic functions, known as map algebra. This procedure provides the ability to perform map layers mathematically that is important for the modelling in which various maps are combined using various mathematical functions. Conditional operators that are used here are: = eq (equal), ≠ ne (Not equal), < lt (less than), <= le (less than or equal), > gt (greater than), and > = ge (greater than or equal). Many softwares/systems can handle both vector and raster data.

Two-map overlays with some basic arithmetic and Boolean operators are powerful tools for examining and spatial patterns caused by interaction of one with another. In generating a two-map overlay, the goal is to combine the inputs according to a set of rules (the map model) that determines for each location the class of the output map from the classes of the input maps. Figure 7.20 shows the example of two input maps and the resulting output map, in addition to a truth table that shows the output map class for each combination of input map classes and a series of statements in the map modelling. The *impose operation* is useful for restricting the areas on an output map according to a binary map that acts as a mask. Often the binary is used as a base map to define the extent of the study. The joint operation is used for overlapping map sheets together in a single operation as shown in figure. The conditional statement contains more than two expressions and execution continues from left to right until an expression is satisfied. Thus if four maps, B1, B2, B3 and B4 are combined the conditional statement might read as:

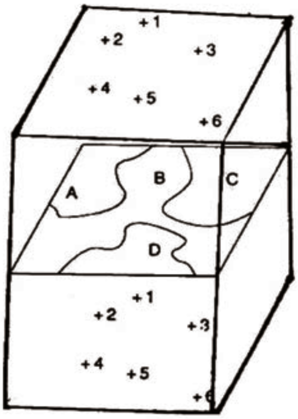
$$C = \{ B1 \text{ if } B1 > 0, B2 \text{ if } B2 > 0, B3 \text{ if } B3 > 0, B4 \}$$

which would cause B1 to take precedence over B2, B2 over B3 and B3 over B4 in the joint operation. Special editing software for correcting mistakes along seams between adjoining sheet maps fail to link up perfectly. Where such operations are carried out in vector mode, edge matching can be accelerated by semi-automatic methods. A simple method for comparing two maps that have the same number of matched classes is controlled by the following modelling statements



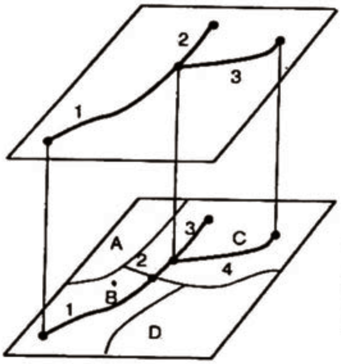
Newcover	Cover1	Cover2
1	1	A
2	2	A
3	2	C
4	1	B
5	2	B
6	2	D
7	3	B
8	3	D
9	3	C

Polygon overlay



Point ID	V1	V2	V3	Poly ID	V6	V7
1	1	1	1	B	1	1
2	2	2	2	A	2	2
3	3	3	3	C	3	3
4	4	4	4	B	1	1
5	5	5	5	D	5	5
6	6	6	6	B	1	1

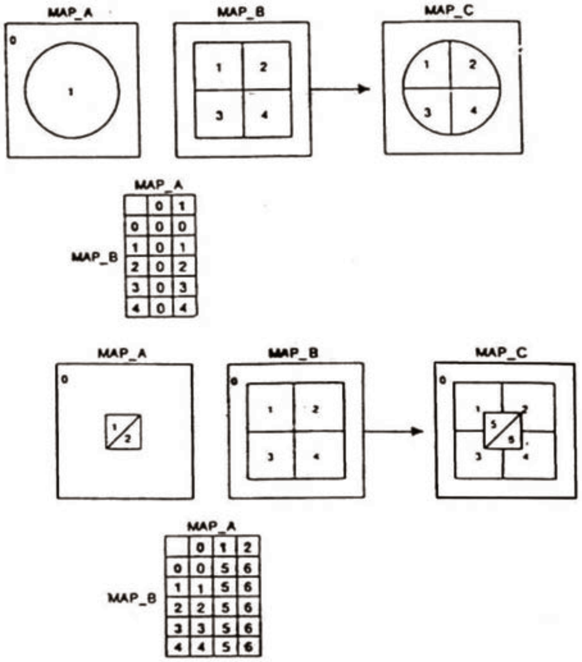
Point-in-polygon overlay



line-in-polygon

Line ID	Old Line	Poly
1	1	B
2	1	C
3	2	C
4	3	C

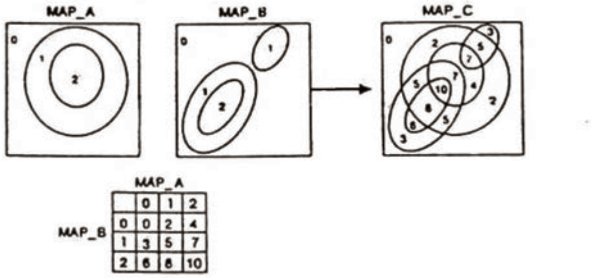
Fig. 7.19: Overlay of thematic layers.



		MAP_A	
		0	1
MAP_B	0	0	0
	1	0	1
	2	0	2
	3	0	3
	4	0	4

		MAP_A		
		0	1	2
MAP_B	0	0	5	6
	1	1	5	6
	2	2	5	6
	3	3	5	6
	4	4	5	6

Two-map overlay using Stamp operation



		MAP_A		
		0	1	2
MAP_B	0	0	2	4
	1	3	5	7
	2	6	8	10

Two-map overlay illustrating the weighted sum

Fig. 7.20: Two input maps and the resulting output map – stamp operation and weighted sum.

Get input map classes as earlier

A = class (‘MAP_A’)
B = class (‘MAP_B’)

The result is A if A equals B

$$C = A \times (A = B)$$

The expression (A = B) has the value 1 if the equality is true

Otherwise it has the value 0

Result is (C)

This immediately reveals where the two maps are the same, where they differ and which classes show the greatest correlation. Weighing and adding the individual class values can sometimes usefully combine two maps. Suppose that MAP_A and MAP_B in Fig. 8.9 are geochemical anomalies, but that MAP_B is more important than MAP_A, then the coincidence of the two sets of anomalies might be modelled with the following statements:

Get input classes as earlier

A = class ('MAP_A')
B = class ('MAP_B')

A is weighed by a factor of 2, and B by a factor of 3

C = 2 × A + 3 × B
Result = (C)

Boolean and arithmetic operators illustrate the flexibility of using map modelling to combine maps together. The modelling statements are:

Get input map classes

A = class ('MAP_A')
B = class ('MAP_B')

Use a conditional statement that reads C is set to

A if B equals, else to B minus 1 if B is greater than 0, else to zero

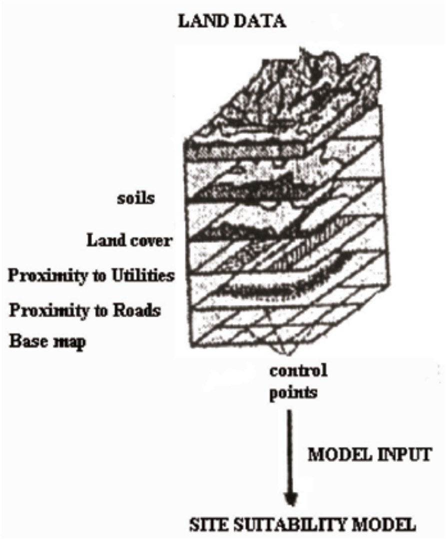
C = (A if B = 2, B – 1 if B > 0)
RESULT (C)

Matrix overlay available in some systems allows complete flexibility of assigning output classes in terms of the input class combinations. Combination of classes from the two input maps is assigned an output class in a two-dimensional array exactly comparable to the truth tables showing for the preceeding combination methods.

7.9 Modelling

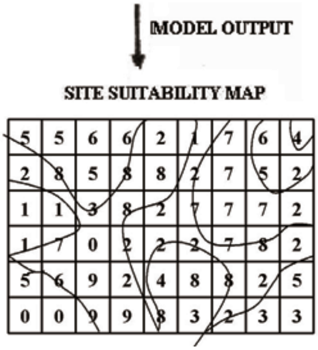
Weighing and Rating

It is a technique which provides a mathematical method to analyze and construct a map from overlays or data from other related or unrelated maps. It provides us with a method in which we can compare or rate. The factors (data layers) are identified and types within these factors are assigned values on separate scales. Each factor is given a weight or multiplier, which is to represent that factor's importance relative to the others (Fig. 7.21). The values for each type in a factor are then multiplied by the weight for the factor and the sum of the multiplied values is the rating for that analysis.



Attributes	Entities and Weights				Attribute weight
Soil	Flood plain-0	Clay upland-5	Load rolling upland- 2	Load dissected upland- 3	10
Land cover	Crop Land- 5	Hard wood-2	Pasture- 4	Firewood- 3	6
Utilities	Electric only-2	Water only -3	Gas with water- 9	Electric & water-5	8
Proximity to major roads	Within cell - 2	Cell- 3	Cells-2 to 5	5-10 Cells- 2	7
Slope	0-2 %	2-5 %	5-8%	8-12 %	7

Legend : 0- Unsuitable , **9-** Most suitable ;



5	5	6	6	2	1	7	6	4
2	8	5	8	8	2	7	5	2
1	1	3	8	2	7	7	7	2
1	7	0	2	2	2	7	8	2
5	6	9	2	4	8	8	2	5
0	0	9	9	8	3	2	3	3

Fig. 7.21: Weighing and rating approach.

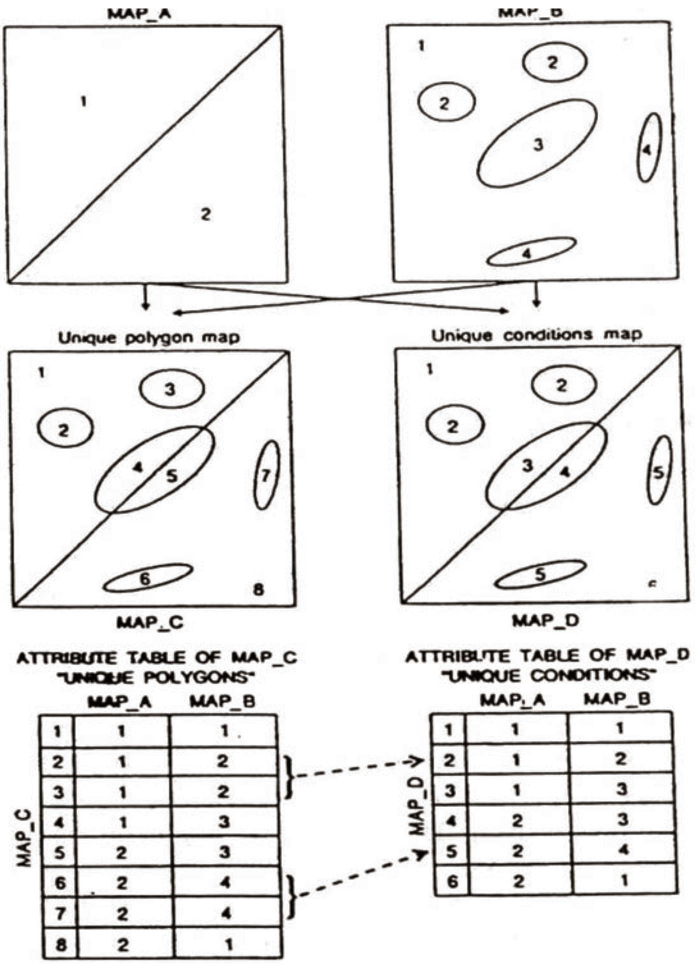
Interpolation

Prediction of unknown values using known values at neighbouring locations by mathematical function is to derive missing point values with existing point values. The accuracy of interpolation depends on accuracy, number and distribution of known points and the performance of mathematical function. Kriging is one method used for interpolation. *Kriging* uses the previous equation of verse weights. One of the assumptions of ordinary kriging is that the mean of the variable is stationary and does not show spatial trends. In practice, the variability of most surfaces can be decomposed into three components: a trend component (drift), spatially auto correlated component (signal) and a noise component – the unexplained residual variation. The trend component can be modelled separately by trend surface analysis. One way of dealing with spatial trends is to carry out a trend surface analysis (Fourier series analysis), remove the drift component before kriging (Agterberg, 1974) and add the trend back afterwards. Alternatively apply universal kriging that combines trend surface analysis and ordinary kriging into a single operation so that the trend and signal are estimated together. However, the weights are calculated from a set of (n + 1) simultaneous linear equations where n is the number of points used for the estimation at any one location as before (Isaacs and Srivastava, 1989).

Map Modelling with Attribute Tables

The modelling language is employed to combine two input maps having attribute tables. The modelling language can utilize not only map classes but also items in attribute tables, at records that are linked to spatial objects on the map by a key field**.** Figure 7.22 is a geological map that is to be combined with a geochemical map (the polygons could be catchment basins). Each map is linked to an attribute table by map class. There are three fields in the geology table, the first being the class number (key field providing the link to the map also called geology), the second being a lithology code and the third being an age code. The table called geochemistry is a polygon attribute table with four fields: a key field (providing a link to the map called geochemistry) and three fields for geochemical elements. The goal is to produce a new map classified into two classes; the first class consists of those areas that have an age code of 4 and value of greater than 140 ppm. The second class contains all the remaining areas. Map modelling pseudocode to carry out this operation is as follows:

```
Get the class values for the geology and geochemistry maps at the current location
        GEOL = class ('GEOLOGY')
     GEOCHEM = class ('GEOCHEMISTRY')
Lookup the age code in the geology table for this map class
The expression "table ('A', 'B', 'C')" means
     Agecode = table ('Geology', 'geol', 'age')
```



ATTRIBUTE TABLE OF MAP_C
"UNIQUE POLYGONS"

	MAP_A	MAP_B
1	1	1
2	1	2
3	1	2
4	1	3
5	2	3
6	2	4
7	2	4
8	2	1

ATTRIBUTE TABLE OF MAP_D
"UNIQUE CONDITIONS"

	MAP_A	MAP_B
1	1	1
2	1	2
3	1	3
4	2	3
5	2	4
6	2	1

Fig. 7.22: Input maps and attribute table combinations.

Lookup the zinc values in the geochemistry table for this polygon

ZINC = table ('geochemistry', geochem, 'Zn')

Set output to I if conditions are satisfied else set to 0

OUT = (1 if Agecode = 4 and ZINC > 140,0)

OUT is the class value of the new map

Result is (OUT)

It is the data extraction: Of facts embodied in a dataset in the form of patterns and associations on maps that help to characterize, understand and predict the spatial phenomenon. This understanding is essential for interpretating various drought indicators for assessment and monitoring.

7.10 Web-based GIS

Large volumes of digital spatial data have been created using GIS, Computer-Aided Design (CAD) and image processing systems. There is a need to visualize and explore these data for human development activities. Virtual Reality (VR) technology and the Internet have provided opportunities to satisfy these needs, as they are for data representation, interaction and dissemination. The Internet and World Wide Web (WWW) have experienced a phenomenal growth in recent years and web is now being widely used as a distributed computing environment. The integration of GIS, VR and the Internet facilities complement each other in facilitating the exploration of spatial databases. The capability of 2D GIS as described in this chapter with its spatial database, analytical functionality and visualization could integrate with VR-computer graphics technology that emulates the real world in three dimensions and provide virtual environment. A number of approaches that are possible are shown in Fig. 7.23.

Internet GIS is the combination of the Internet and GIS that is a conventional GIS using the Internet as a basic information infrastructure for spatial data dissemination. Because of the nature of the Internet, Internet GIS is regarded as an interactive, distributed, dynamic, cross-platform and client server computing system and it has the capability to access various forms of GIS data and functions in an inter-operatable environment (Peng, 1999). There are two types of architectures for developing Intern-based GIS

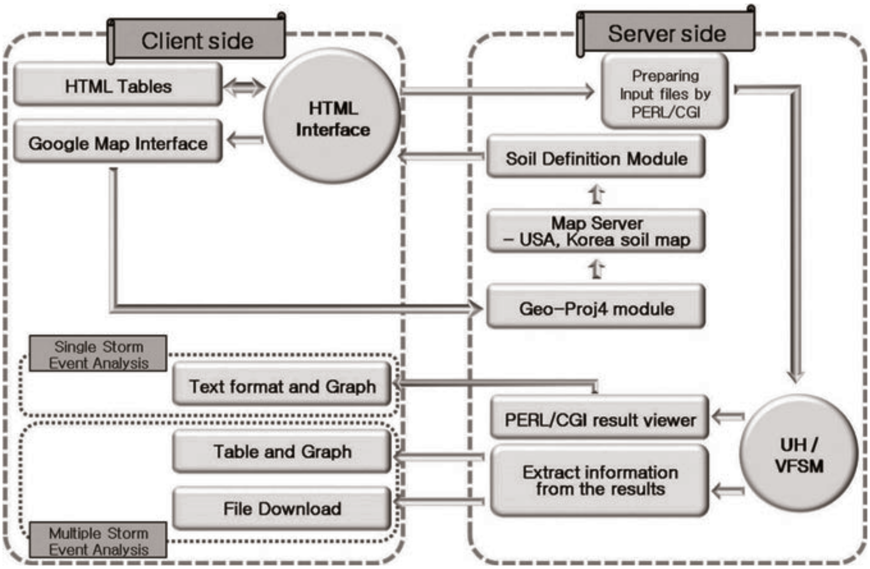


Fig. 7.23: Web GIS.

application for drought: client side and server side. In a *client-side Internet GIS* (Fig. 7.24), the client (Web browser) is enhanced to support GIS functionality while in server-side application, a web browser is used only to generate server requests and display the results. Client-based GIS runs on a Java applet and the code for applet is transferred to the Web browser as binary instructions that provide a graphical user interface (GUI) for the GIS application. Vector-based data is then transferred to the client enabling the complex GIS functions on the client. In server-side GIS, a Java applet creates a GUI for the GIS application and it acts as an interface for an image. The complex GIS calculations and the data remain on the server. In either case, the desired software (Java-applet, ActiveX or plug-ins etc.) needs to be transferred to the user. In *server-side internet GIS* (Fig. 7.25) user sends a request to a server (i.e. an address) and the server processes the request and sends the results back as an image embedded in an HTML page via standard HTTP. Web browser can view the response. All the complex and proprietary software, in addition to the spatial and tabular data remains on the server. The advantages and disadvantages of client-side and server-side architectures can also be tabulated.

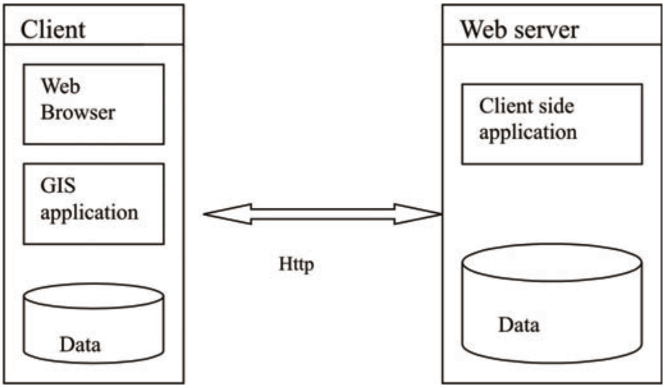


Fig. 7.24: Client side internet GIS.

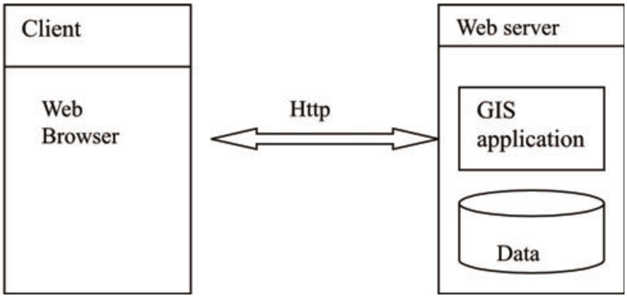


Fig. 7.25: Server side internet GIS.

The system is designed with three distinct components: a server application, a client interface and a data repository. This multi-tiered layered architecture is shown in Fig. 7.26. The client layer consists of a personal computer running a web browser that provides the user interface and operates by generating requests to the application server via HTTP and displays the resulting HTML file in a web browser. The middle layer consists of web server layered on an application server. The web server receives requests from the client, which are processed by the application server's web administration module (MoIMS Web Link), then passed on to the application server. The application server makes requests to the data layer via TCP/IP and ODBC. The data layer is a data repository consisting of a relational SQL compliant database and one or more directories of flat files in ESRI shape file format. The data repository is built and maintained through an off-line data migration process that involves updating the data tables with new data and geo-coding new shape file. Data migration is an integral part of the system and is included in the overall system. The map application processes data and generates HTML files, which are in turn served to a client PC running a web browser. The hardware and software configurations that can support this system were designed by Jony Marshall (1999).

Spatio-temporal geo-representations can handle two dimensions of space of different time; four-dimensional GIS designed for three dimensions of space and time. Multimedia/hypermedia GIS allows the user to access a wide range of geo-referenced multimedia data (e.g. simulations, sounds and videos) by selecting resources from a geo-referenced image map base. A map serving as the primary index to multimedia data in a multimedia geo-representation is termed a hypermap. Multimedia and virtual geo-

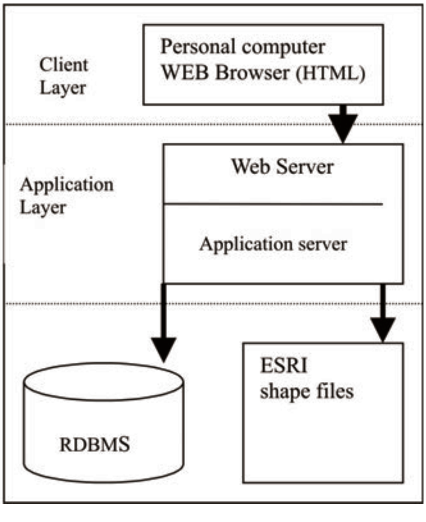


Fig. 7.26: Multi-tiered system architecture.

representations can be stored either in extended relational databases, object databases or in application-specific data stores. Multimedia atlas was developed for the tourist information system in China by Raper (2000). Imagine having a real-time (using telecommunication links) multimedia GIS can audio-visually monitor different locations at the same time. Since video is a spatio-temporal projection of the world in imagery, it can be considered to be capable of fully multi-dimensional geo-representation. It can be used for mapping from moving platforms for target positioning, for the measurement of geo-phenomena.

VR GIS is used to represent the combination of VR and GIS technologies that is a conventional GIS with VR as the main interface and interaction method. Because VR provides a rather realistic representation of the world, it can be a nice complementary tool for existing GIS. It is widely used in environmental planning, scientific visualization, military simulation etc. It can also be a web-based GIS. *Real-time GIS* would help to monitor the transmitted record and anlysis of the movement of vehicles, people or animal. Some applications can monitor the proximity of the mobile agents to specified locations or intimate them on alternative routes based traffic reports. Real-time GIS can also include location-based services (Raper, 2000).

Networked GIS – Prior to Internet VR models were standalone like CAD models. The VR models can be networked and participants can be involved in VR by logging in a network computer. More details about the networked VR and associated techniques are given in Singhal and Zyada (1999). A complete integration of these three provides many advantages for setting up a platform for distributed spatial decision-making. Commercial VR tools such as Pavan (VRML compiler and project management of MapInfo GIS) VirtualGIS – an add-on application for 3D visualization and analysis to ERDAS Inc's IMAGINE and ArcView 3D analysis (ESRI Inc.1997a) are available for creation of 3D VRML models from GIS data. The VRML compiler and project management system in the software creates navigable 3D (VR) models generated from the data held in GIS. The resulting models can be represented by VRML and viewed interactively in most recent versions of the web browsers (Huang et al., 2001). ArcView has a set of extensions such as Internet Map Server (IMS: ESRI, 1997b) and 3D analyst. As an extension, IMS enables users to put maps and interactive mapping applications on the web. A user can employ this extension to provide information services based on dynamic maps and GIS data. The 3D-analyst extension allows users to create, analyze and display surface data. It, however, has not been accomplished on the Internet.

The spatial data on the drought monitoring parameters derived from various sources in space and time could be used as a drought information system, as a part of decision support system. Further networking of site-based data collection platform and on-line processing and dissemination of early warnings to target groups. The drought management practices that are used by different countries and the global drought monitoring activities are discussed in the next chapter.

7.11 Creation of Spatial Data Base in Kolar, India

Spatial data base is created with a view to develop geo-referenced information from various maps (prepared using different techniques in time and space) and point source information that could be compared with each other using GIS as a platform. This region is declared as drought affected area (Southern Peninsular portion) at every alternate year. Annual rainfall of 500 mm is received from southwest monsoon. There exists inconsistency in number of rainy days. Maximum temperature is about 40-45°C. Depth to ground water varies from 200 m onwards. Tanks are not filled due to insufficient rainfall, poor run-off and obstruction to channels. Groundwater dependency from the hard rock aquifers (highly unpredictable) is very high. Unit area of micro-level planning in India is based on Revenue villages (group of sattlements and agriculture land; human population ranges from 200 onwards and total village area from 1.0 sq km onwards) and macro-level by Tehsil/Taluk/Mandal (group of Revenue villages); area level planning by Districts (group of Tehsils) and region level by States (group of districts). The water availability and demand from the crops and population were estimated by synergistic use of remote sensing, ground-based data collection etc. The spatial information-line (drainage, road network) were digitized and created a digital image base using ArcGIS-9.2 software for Gauribidanur/Kolar area of Karnataka, India. The land use and cover information (polygon) and point data (well, population etc.) were treated in the same way. The necessary attribute table was created. The drainage layer and village layer were combined. Paper maps are scanned, digitized; geo-referenced and created a spatial base. The information that are collected from amps are: Surface transport (road and railway) network that is needed in planning the transportation of food supply and water during drought situation (Fig. 7.27); Drainage network (natural drainage with stream order) in understanding the run-off characteristics, canals and surface storages (lakes, ponds, reservoirs) in assessing the existing storage capacity (Fig. 7.28); Revenue village boundaries (settlement and farms, plots and other public related areas – grass land, hills etc. of one settlement or groups identified for revenue related activities), human settlements within the boundary and tehsil/mandal (revenue unit indicating the group of revenue villages) (Fig. 7.29); Geology (rock types) in understanding the aquifer characteristics) (Fig. 7.30); Spatial distribution of tanks and ponds (Fig. 7.31); Buffer zone around tanks (Fig. 7.32); and Villages depend on surface storage systems – Tanks of varied size (Fig. 7.33) or ground water (Fig. 7.34). Their dependency for irrigation from the said sources is illustrated. The digital contour information

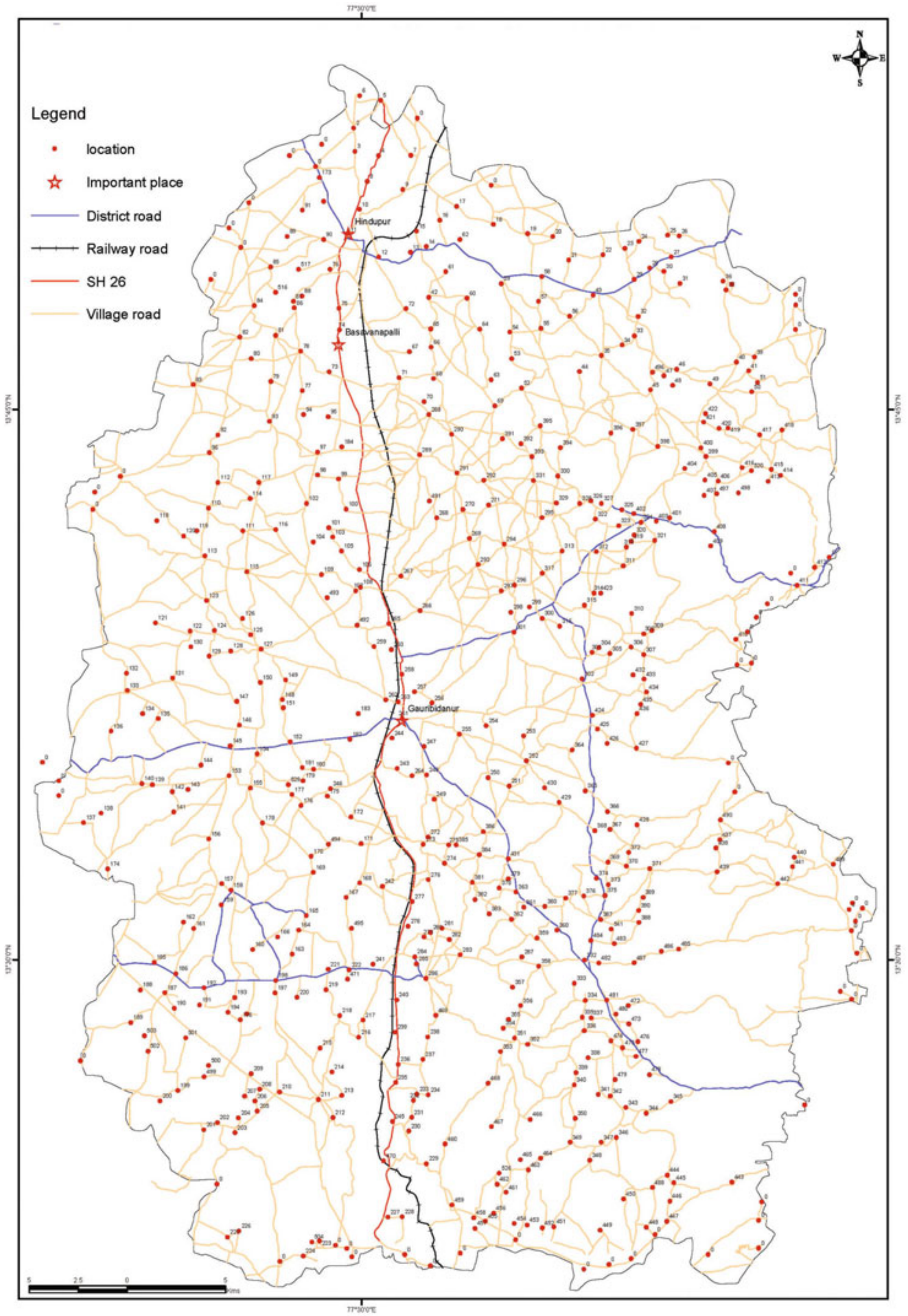


Fig. 7.27: Surface transport network, Kolar.

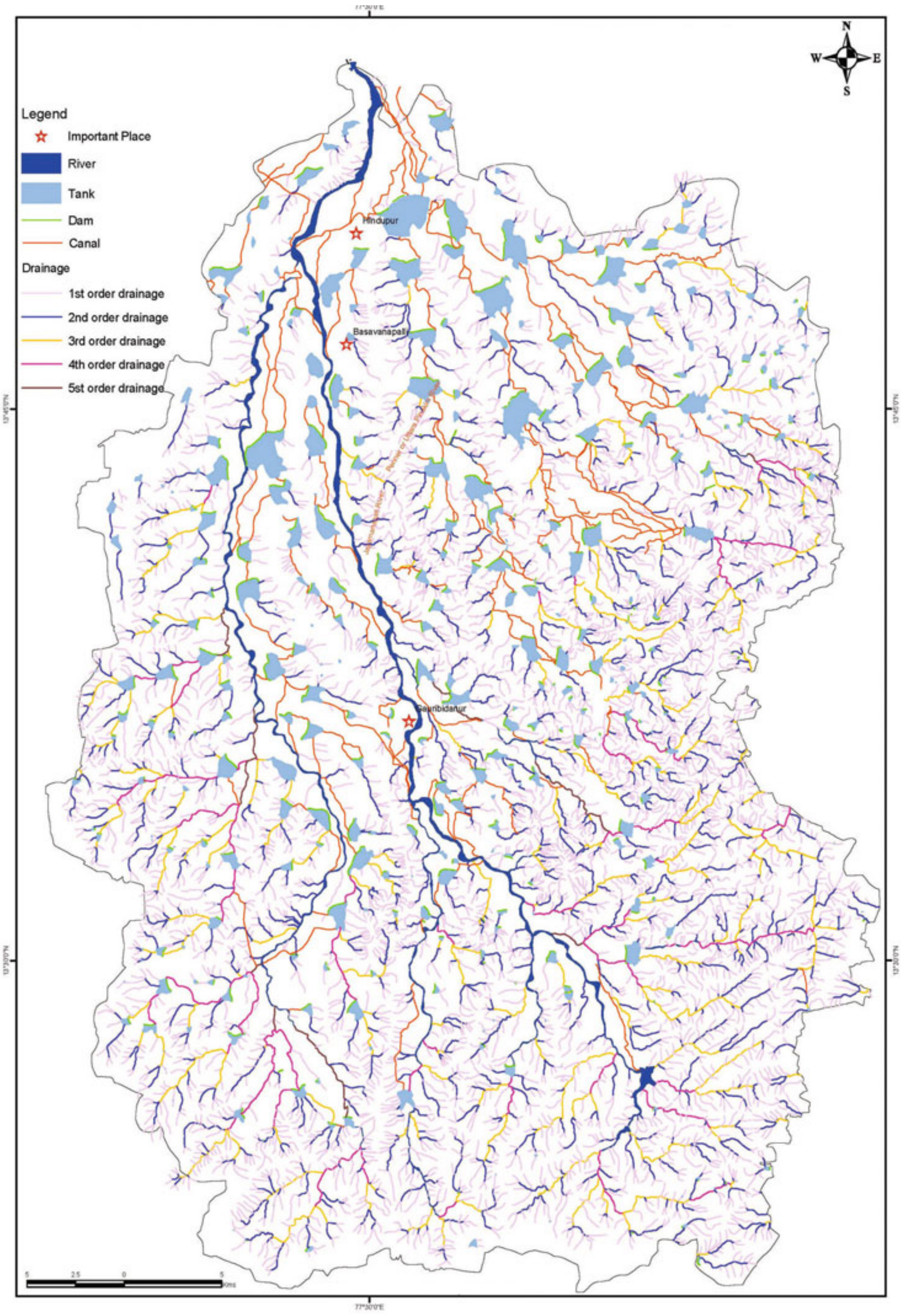


Fig. 7.28: Drainage network and surface storages.

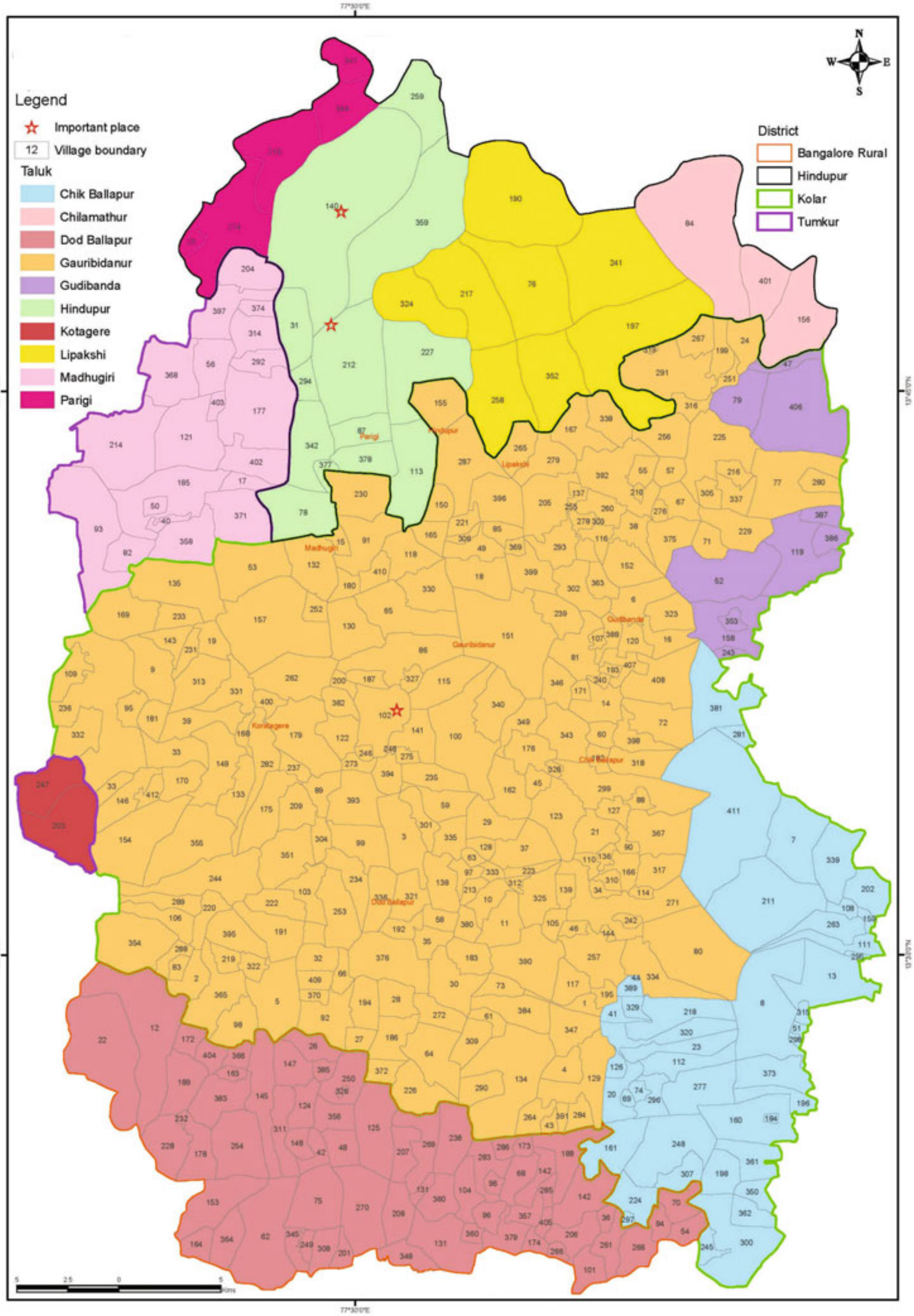


Fig. 7.29: Revenue villages, settlements and tehsil boundaries.

Source: Census of India, 2001

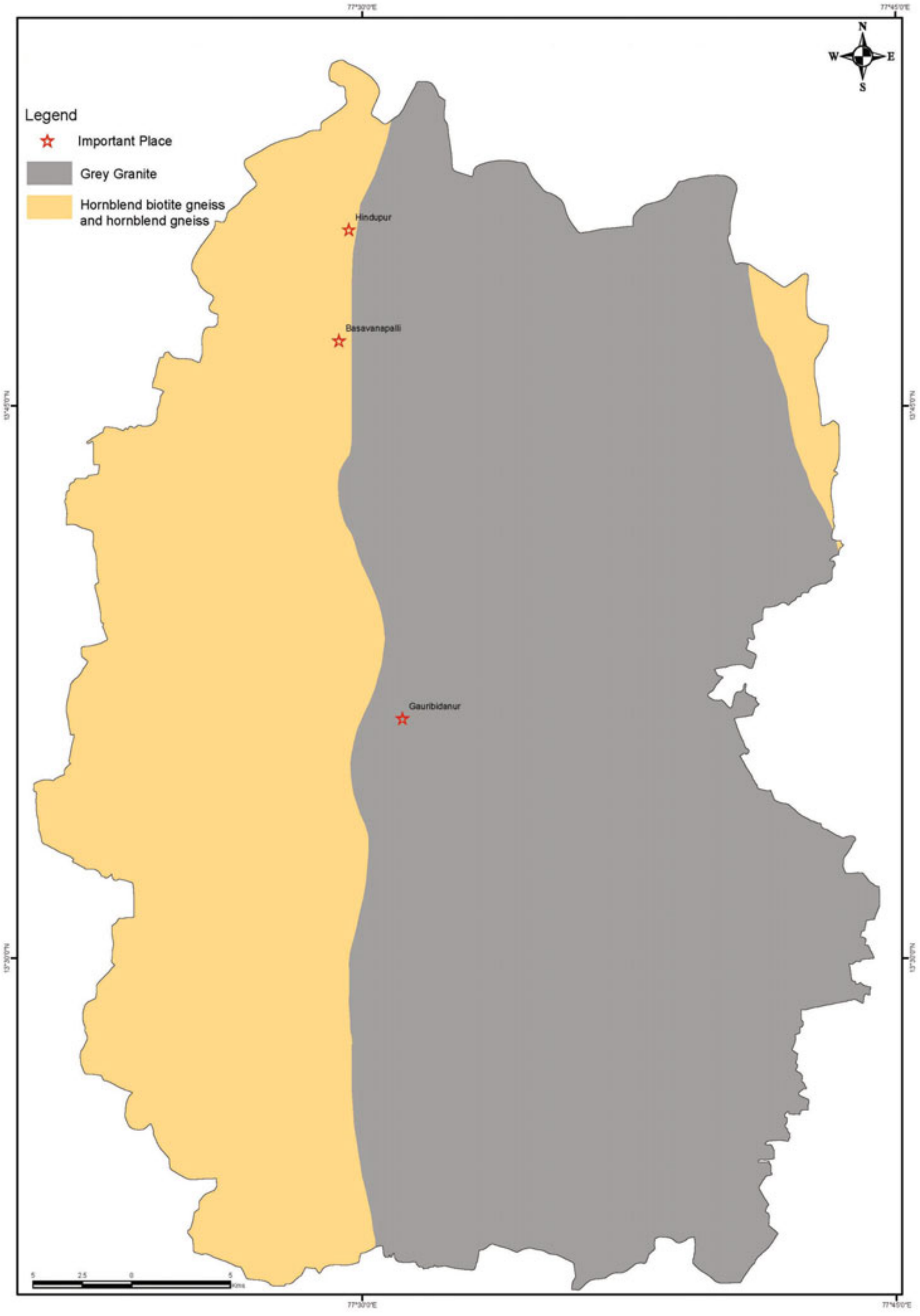


Fig. 7.30: Geology.

Source: District resource map

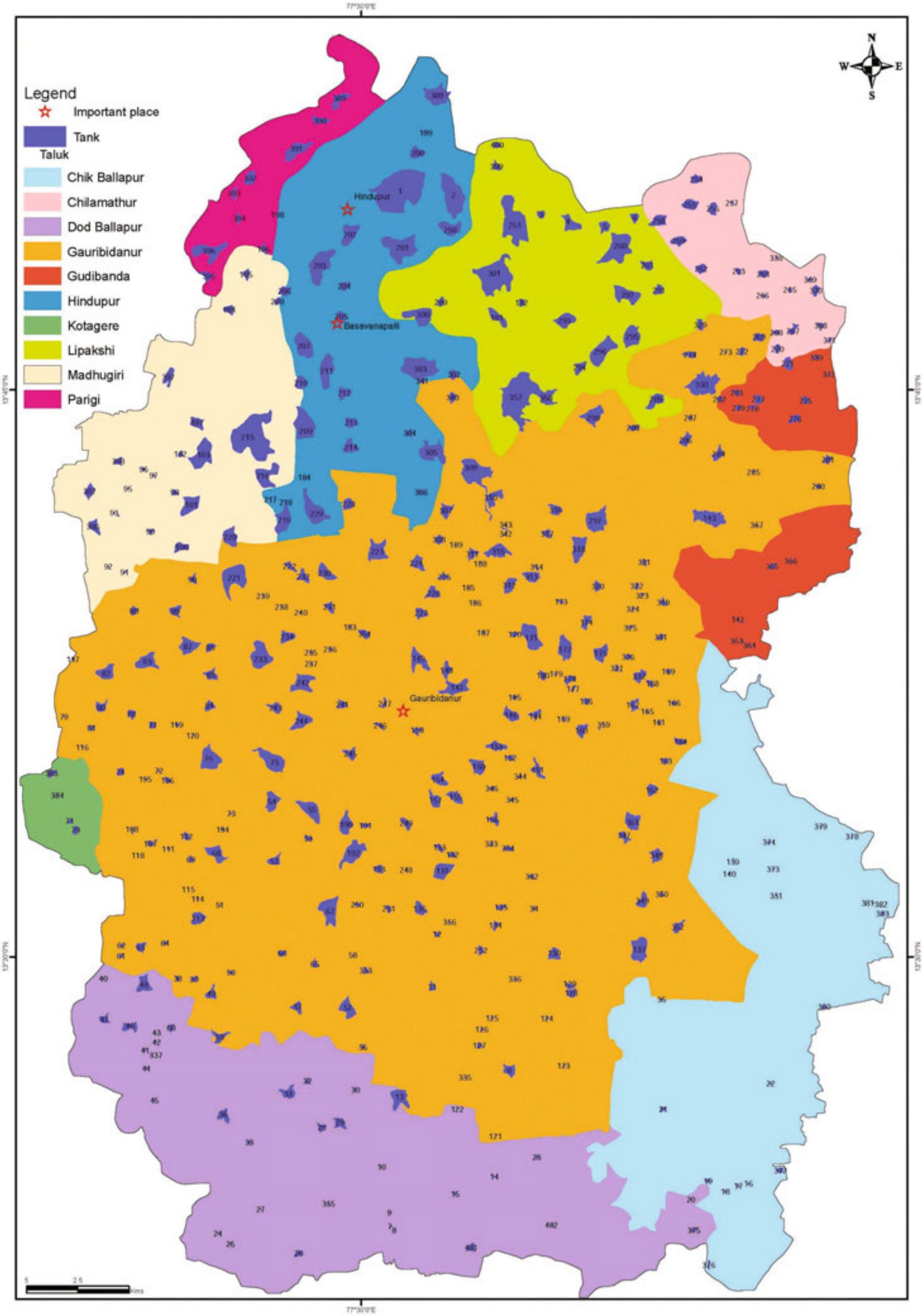


Fig. 7.31: Spatial distribution of tanks and ponds.

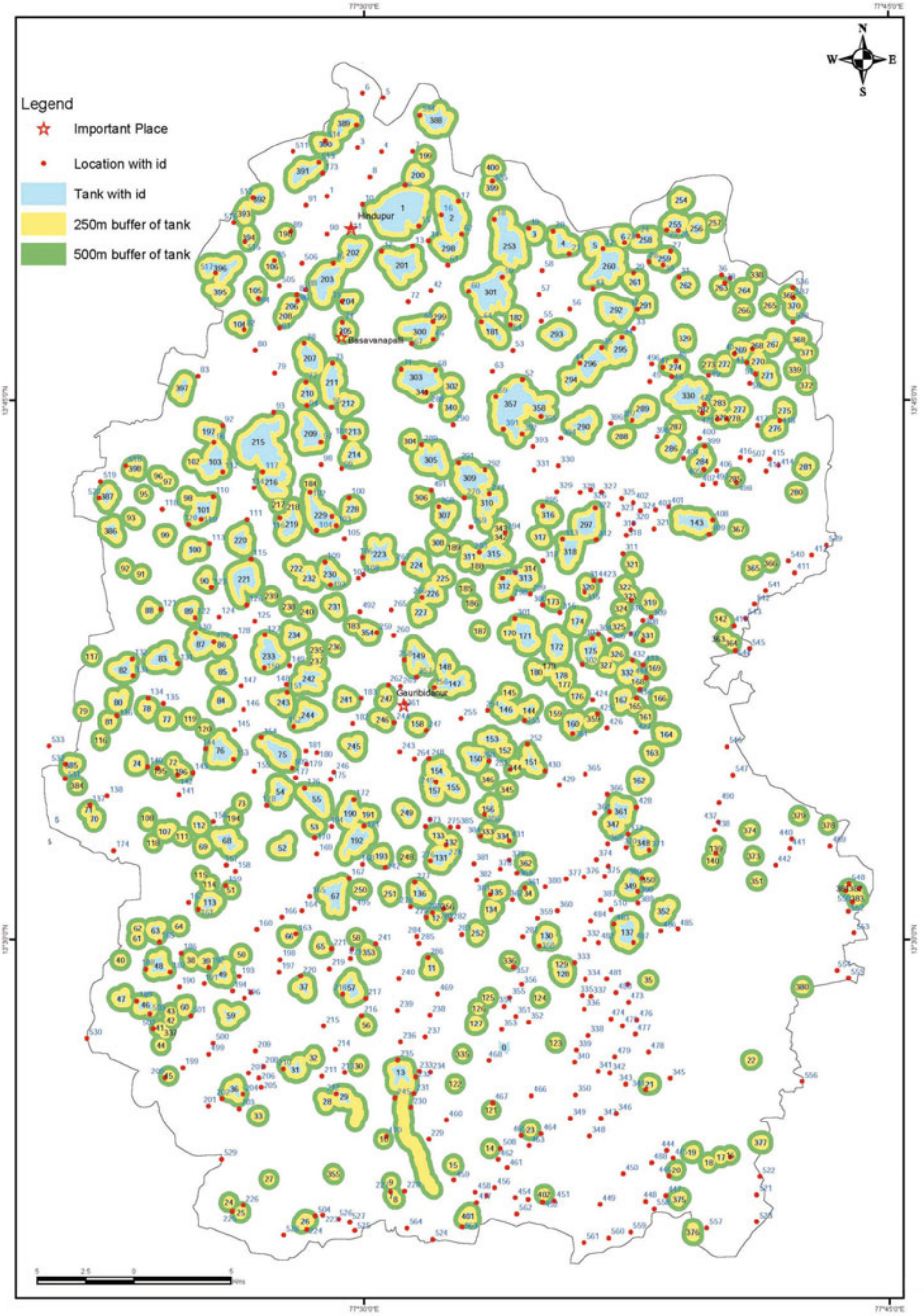


Fig. 7.32: Buffer zone around tanks.

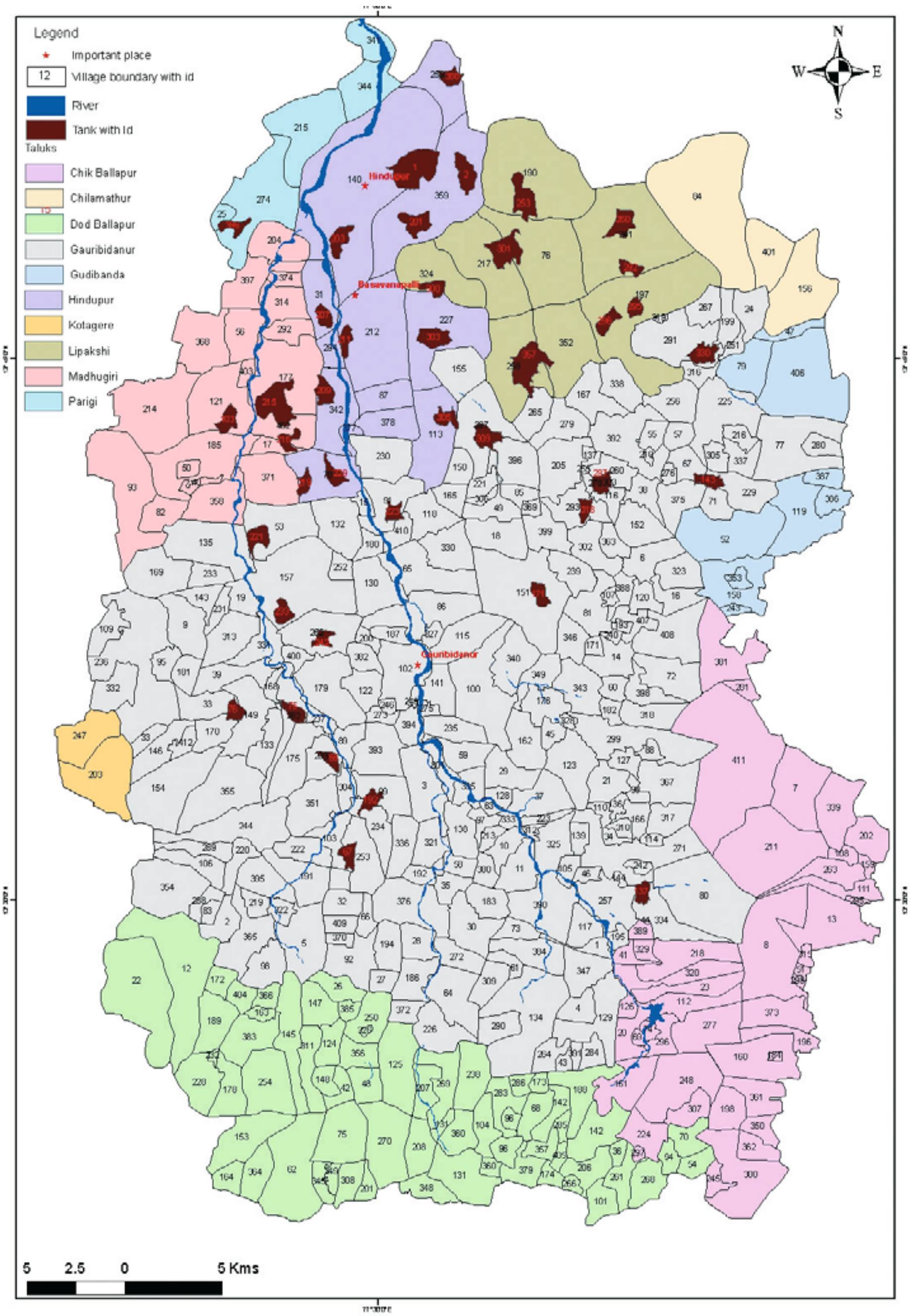


Fig. 7.33: Prioritization of surface water bodies (major) for rehabilitation.

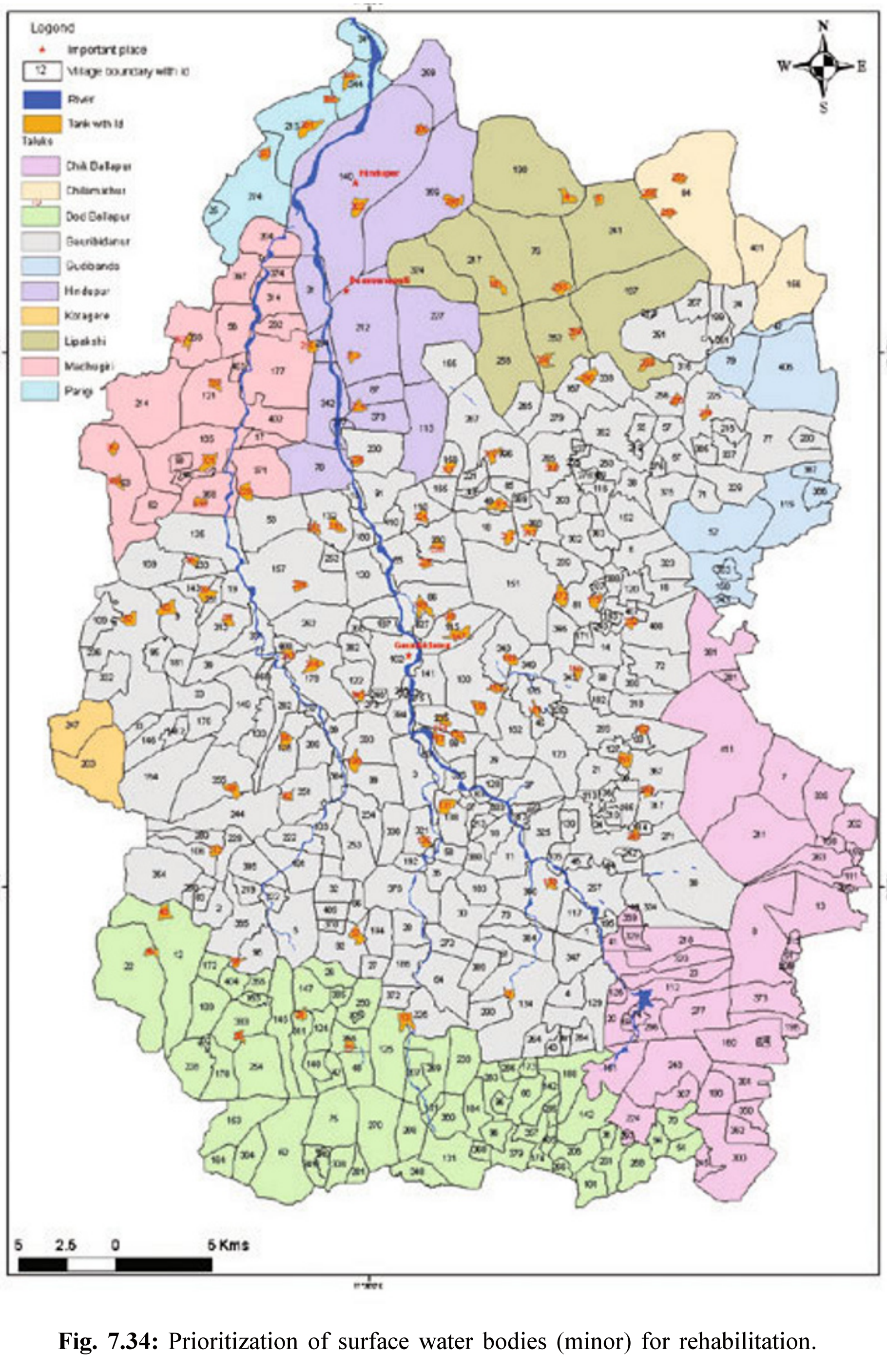


Fig. 7.34: Prioritization of surface water bodies (minor) for rehabilitation.

was also used in the generation of slope profile and aspect. Based on the water supply (run-off and ground water) and demand (crop, human requirement) model, the requirement and deficit from the monsoon rainfall (June-September) for the individual villages were calculated. The collected information was also used in assessing drought condition through weighing and ranking method. Weight is assigned to each parameter that reflects the importance in the event occurrence together with the rating for the individual classes that denotes the event intensity. The class intervals are derived from the observed event severity of the past. The various parameters of significance were grouped into: frequency of events (historical); climate (time series of rainfall, rainfall fluctuation, evaporation, aridity); resource availability (vegetation cover, food-crop area, cash crop, water-surface and ground water); demand (population density, growth, industry); distribution loss (surface storage, medical facility, system efficiency) and sharing of resources (proximity to infra-structure facility) etc. Even though all these factors are inter-related, the weights of these factors were assigned based on the observed deficits.

The scale of information requirement varies with *Action Levels* which provide a basic framework from which to take actions to assess, communicate, and respond to drought conditions. Five general action levels related to drought conditions are: *Normal* (routine data collected and distributed), *Advisory* (heightened vigilance with increased data collection), *Watch* (increased assessment and proactive education and water restrictions depending on the capacity of each individual water supply system), *Warning* (severe situation and the possibility that a drought emergency may be necessary) and *Emergency* (mandatory water restrictions or use of emergency supplies). It is a general plan of action to coordinate statewide response to drought situations. Figure 7.35 highlights the information requirements for drought analysis. Individual agencies and communities have a range of actions for implementing and managing their own system during drought based on the micro-level studies.

Knowledge Base stores the knowledge and expertise required for DSS. This is transformed into a number of facts and rules and their corresponding actions for the different combinations of each objective's attributes. Rule Based System (RBS) is a computerized system that uses knowledge about some domain to arrive at a solution to a problem from that domain. It is grouped into various stages of development such as: (a) problem definition and expert selection, (b) knowledge engineering (climatolgical, hydrologic and hydrogeologic attributes, agriculture attributes, and socio-economic attributes, (c) interference engine and (d) verification and validation. Problem definition and expert selection is critical because it provides the basis of the remainder of the RBS.

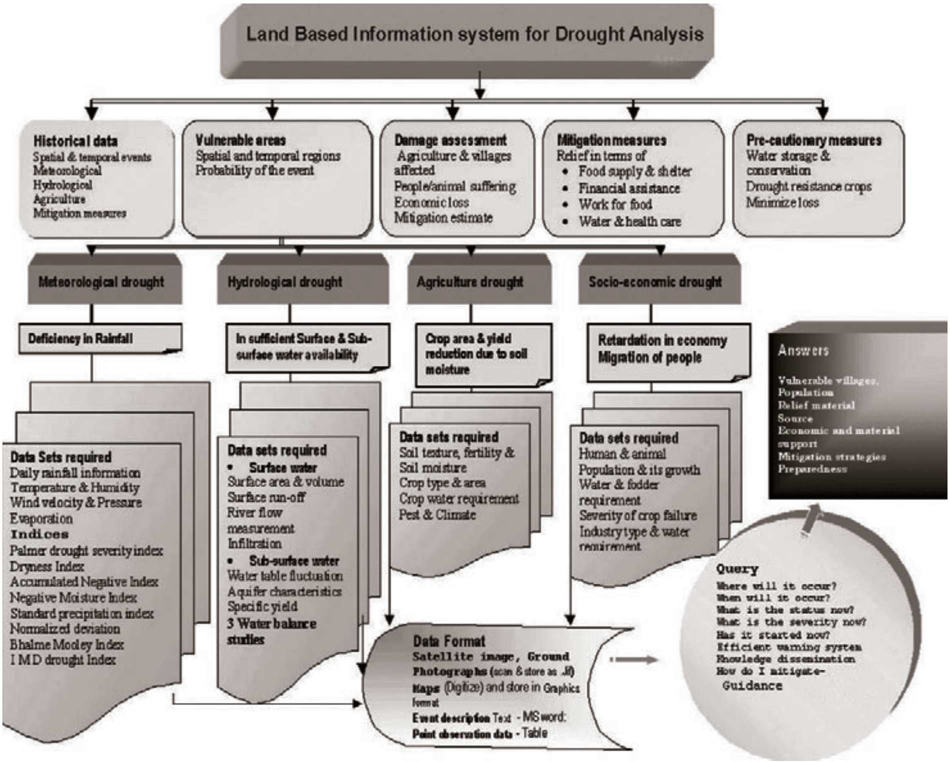


Fig. 7.35: Land-based information system for drought analysis.

An expert system attempts to reproduce the performance of one or more human experts, most commonly in a specific problem domain, and is a traditional application and/or subfield of artificial intelligence. A wide variety of methods can be used to simulate the performance of the expert. However the common problem to most or all are (1) the creation of a so-called "knowledge base" which uses some knowledge representation formalism to capture the Subject Matter Experts (SME) knowledge and (2) a process of gathering that knowledge from the SME and codifying it according to the formalism, which is called knowledge engineering. Expert systems may or may not have learning components but a third common element is that once the system is developed it is proven by being placed in the same real world problem solving situation as the human SME, typically as an aid to human workers or a supplement to some information system. As a premier application of computing and artificial intelligence, the topic of expert systems has many points of contact with general systems theory, operations research, business process reengineering and various topics in applied mathematics and management science. The most common form of expert system is a computer program, with a set of rules that analyzes information (usually supplied by the user of the system) about a specific class of problems, and recommends one or more courses of user action. The expert system may also provide mathematical analysis of the problem(s). The expert system utilizes what appears to be reasoning capabilities to reach conclusions. Wizard is an interactive computer program that helps a user solve a problem and the term was used earlier for programs that construct a database search query based on criteria supplied by the user. However, some rule-based expert systems are also called wizards.

7.12 Decision Support System

Decision Support System is a computer-based information system consisting of hardware/software and the human element designed to assist any decision maker at any level. It assists the manager in his decision-making process for semi-structured tasks, support the management, improve the effectiveness of decision making rather than its efficiency etc. Structured and unstructured decision problems have been in the core of the concept of decision support system (Simon, 1966). The efficient DSS would take care of the decision processes and the user's requirement. There is a need to define the current decision to be supported, objective and probable result from the system and familiarity of the processes that are being attended by the system. DSS includes a database, model base and dialog management. Database creates, modifies and maintains the data, model base includes mathematical and statistical models to enable DSS to perform any type of analysis and the dialog management is the user/system interface. It has: (a) *flat file model* – files having series of record and fields and no relationship amongst them. Basic operations such as file creation, deletion, and updating and simple data query can be performed. (b) *Relational model* offers flexibility. (c) *Hierarchical model* (known as upside-down tree) is made up of records (nodes) and have several fields, with branches and a root on the top. The nodes with same parents are called twins or siblings. The connections between files do not depend on the data contained within the files. (d) *Rule model*, a knowledge-based or expert-based system, describes set of rules, conditional or unconditional, and provides only queries to user suitable for complex relationship analysis. Model base describes about the real-life situation. It is by defining the problem, constructing the model – creation of variables, constraints, assumption, selection of a forecasting model and decision variables.

DSS generator features

DSS Component	*Spreadsheets*	*Database Managers*	*GIS*
Interface	Tables, forms, charts	Tables, forms, reports	Multi-layer maps, plots
Database	Independent cell entries	Linked database tables	Linked spatial and non-spatial database
Database tools	Rudimentary sort and selection	Comprehensive queries	Spatial query
Models	Built-in mathematical functions, statistical and management science tools	Basic mathematical functions	Basic summarization and network analysis models
Model building tools	Recorded or programmed macros	Macro and database query language	Macro (script) languages, programming interfaces to other programming languages

A large number of models and modelling techniques are being developed to support decision makers. These models are drawn from well-established disciplines of statistics or management sciences and in most cases do not require the use of spatial data. The decision makers have a variety of other factors to weigh up, however, and techniques such as multi-criteria decision making like the Analytical Hierarchy Process (AHP) might be used to reach a final decision. Traditional model is used to rank the alternatives and spatial operations are needed to identify the impact of the decision.

7.13 Alert System

Drought events always leave behind with massive economic loss, degradation of environment, and food and fodder shortage in addition to starvation. The purpose of a warning system is to inform as many people as possible, in an area-at-risk that a dangerous and/or damaging event is imminent and also to alert them to actions that can be undertaken to avoid losses (Murton, 1991). The external forces always influence the drought events and its intensity that affects the physical/environmental system in addition to social system. The social system responds to the event based on its inherent behavioural pattern influenced by the requirement and availability.

The mitigation activities are guided by the supply and demand measures in minimizing the loss or how to avert or cope with the immediate situation.

The information range includes: (1) Early advisory/alert/warning on the onset of the event, (2) Spatial distribution of the area, severity of the event and the probable duration of the event, (3) Immediate and long-term adoptability guidelines to cope up with the situation, (4) Data about the event for consumption and propagation amidst its members, (5) Ground indicators for validation/confidence measure and (6) Continuous flow of information on the advancement of drought. Every country has its own ways of event prediction, recognition, monitoring, dissemination of information and mitigation efforts (Wilhite, (1996). Sub-systems that are required include: *Alert sub-system* – that monitors and forecasts the event on national and local levels. The scientific information is communicated to national/local administrative people for management. It provides accurate information on impending hazards and their spatial and temporal coordinates and attributes of the event. *Risk information system* generate, risk scenarios and indicates the potential impact on specific vulnerable groups and sectors of the society. Risk is a complex variable related to hazard types and patterns of variability. Vulnerability refers to the capacity of a household/community to absorb loss or damage and recover from them and its patterns are more dynamic in nature. The risk analysis is limited to hazard mapping, showing areas where different levels of hazard can be expected based on the social, economic, institutional and cultural aspects.

Preparedness system indicates the actions required to reduce loss and damage. The success or failure of an early alert/warning system will ultimately be judged by whether the communication of warning information to people at risk leads to appropriate mitigation enabling a reduction of loss and damage. Warning without providing information on what actions to be taken would be counter-productive and create either panic or apathy. Various groups have different perceptions and different strategies to cope with risk. The reaction to warning varies with range of factors. If the strategy contradicts the perceptions of risk and coping strategies of a vulnerable group, then it is likely that it will be ignored or lead to unexpected results. If vulnerable groups have a detailed awareness of risk levels in the areas where they live, it is likely that they already might have developed appropriate coping strategies. Effective successful preparedness needs to be planned in consultation with people at risk and their perception of risk.

Communication system provides timely information on the impending event, potential risk to vulnerable groups and preparedness strategies. The information on impending hazard events, risk scenario and disaster preparedness strategies need to reach the people on time. The information content should include data on the existence of an impending event, its spatial and temporal coordinates and attributes, the pattern of expected loss and damage and the mitigation actions that could be taken. The quality of information should focus on the perception of the people who receive it. The effectiveness of this information will increase if it is issued through an agency that consists of meteorologist, hydrologist, agriculturist, social scientist, remote sensing specialist, spatial information, telecommunication, media specialists, administrators, and crisis management experts and acceptance from people.

Drought Alert Information System (DAIS)

Drought event is activated from the normal condition by the failure of rainfall, followed by soil moisture/agriculture drought and hydrologic drought (severe drought). Similarly the severity decreases with the rainfall, increase in soil moisture/agriculture yield and improvements in hydrology. The time lag between the meteorological and agriculture/socio-economic droughts could be more than a year. The relevant information could be collected from departments, collate them and create an information base. The historical drought information (knowledge base) also forms a part of it. Informative alert message content needs to be prepared in consultation with the media experts. The vernacular languages (avoiding translation mistakes) must address the common peoples' ability to understand and respond. In addition to generation of information and process within the DAIS, it is also important to interact with the departments and institutions that are actively involved in the research and development. Further, these departments also issue warnings in their routine manner. In order to avoid the conflicting alert messages, the co-ordination between the institutions and their input is required. The various agencies that are collecting, analyzing and issuing alert notes to government departments are shown in Fig. 7.36. Further, the alert information should contain message regarding the immediate action, resources conservation methods, assistance programme (financial/technical) and long-term initiatives. Moreover, the departments hoisting their subject domain messages separately should do it in resonance with DAIS site. The national and local level capabilities need to be modified to append with this type of specific disaster systems in visualizing the enormity of the events. The bench marking of the existing early warning systems, if any, need to be evaluated for its performance and to be re-structured in such a way that they make a significant contribution. This review will bring out the organizational structures, decision-making procedures and information flows for early warning system. This would also enable the prioritization of actions. The system needs to be integrated with national and local level disaster management agencies

Once the relief/mitigation operations are underway, a dedicated communication system needs to be set up for transmission on the dynamic changes or emergency requirements from the site. Walkie-talkie and two-way radios

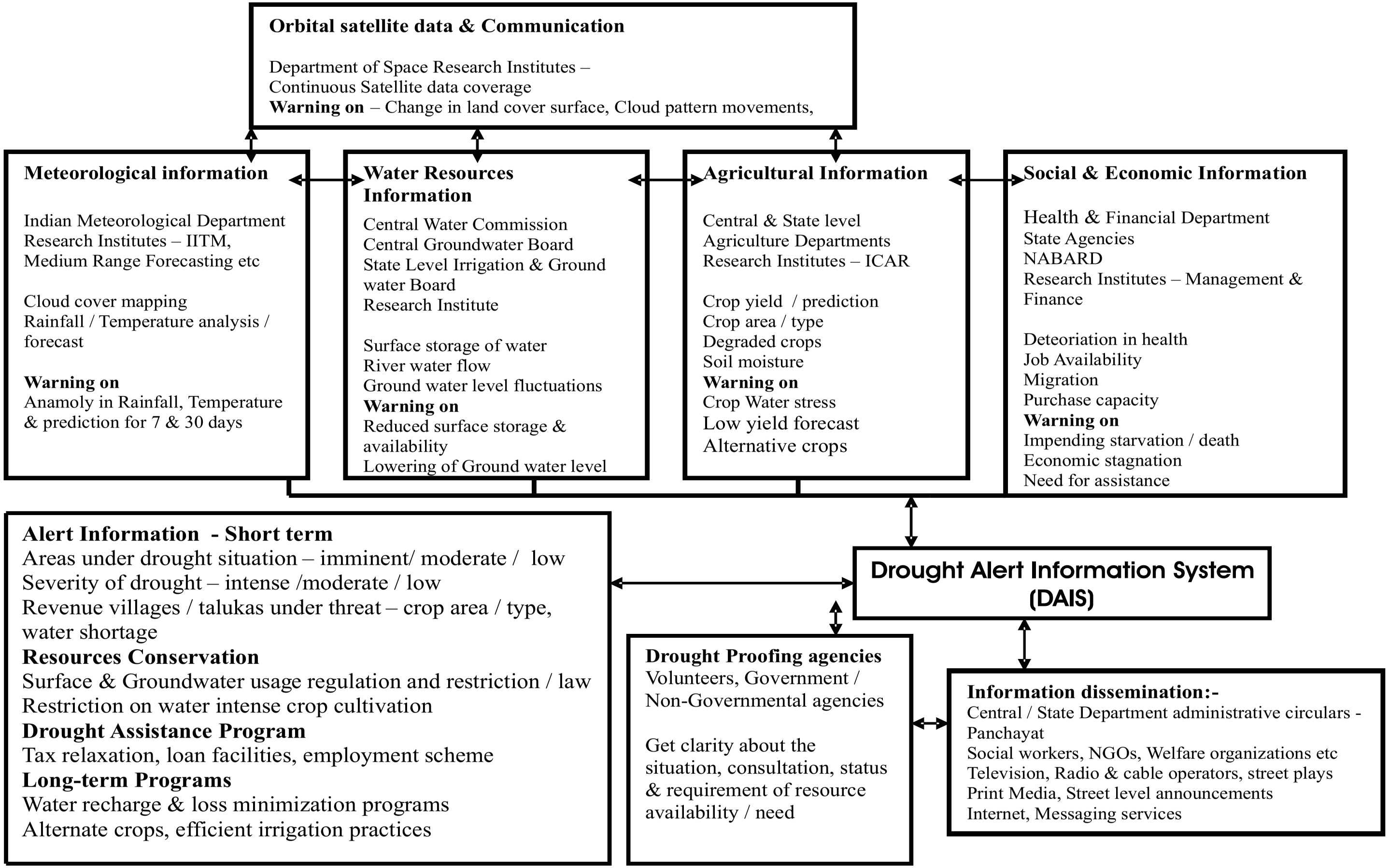


Fig. 7.36: Drought alert information system (DAIS).

have often been used by disaster management organizations elsewhere. VASAT telecommunication facilities for data, voice and information exchange and video conferencing in the state level and VHF wireless network within the districts of Maharashtra are being used in emergency and disaster rehabilitation efforts. DAIS is construed as information base, beside co-ordination and dissemination of reliable, accurate alert information gateway. The huge amount of information gathered need to be stored in a central server as well as in servers located in different parts of the country. The site level (Taluka/ mandal) units would append their monitored data and receive the instruction, so that data is protected. Data sharing and appending protocols can be established using hierarchical method. It will be available for select groups/ users. This approach has taken into consideration the existing/developed systems.

Decision tables are widely used in knowledge-based and decision support systems as they represent relatively complex logic in a familiar and understandable way. Knowledge about the drought could be acquired (considered as a bottleneck) as a procedure or propositional logics and represented in a decision table form. After this knowledge acquisition, contradictory or insufficient knowledge is detected, resolved and the decision table is transformed into if-then-rules or decision trees for reasoning (Vanthienen and Wets). The derivation of first-order decision tables based on the different techniques is the first step (Boolean minimization) in decision-making process. It is interchangeable with other decision models – decision trees, rule-sets, tabular knowledge base and selective relational data bases. Although decision tables are useful and easy to understand, very large tables become difficult to use, manage and comprehend. In a compact second-order decision table, the rows use the sets of values rather than the atomic values of standard (first order) decision tables. Given a database of instances, each labeled by a corresponding class, supervised machine learning aims to find hypothesis (or classifier or predictive model) that correctly predicts the class of unlabeled instances. This algorithm can be viewed as a search for hypothesis that best fits a target function underlying a given data set.

Knowledge Based System (KBS or expert system) is a computerized system designed and developed with user interface (data input and display), knowledge base (acquired knowledge in a specific format), inter-face engine (computations and knowledge matching (rule matching) in reaching solutions), up-date and explanation facility. It is found that knowledge base development is a difficult and time consuming task that needs the cooperation of knowledge engineers and domain experts, decision tables and knowledge needs to be checked for consistency and completeness. Rule-based techniques and representation is preferred by users and visualization of spatial information through GIS is effective.

Management Information System (MIS) is a subset of the overall *internal controls* of a business covering the application of people, documents, technologies, and procedures by *management accountants* to solving business problems. 'MIS' is a planned system of collecting, processing, storing and disseminating data in the form of information needed to carry out the functions of management. It differs from regular information systems which are used to analyze other information systems applied in operational activities in the organization. Academically, the term is commonly used to refer to the group of information management methods tied to the automation or support of human decision making, e.g. *Decision support systems*, *Expert systems*, and *Executive information systems*. MIS differs with *Enterprise Resource Planning* (ERP) as ERP incorporates elements that are not necessarily focussed on decision support. The information requirements in drought management for preparedness, alertness etc. are listed below:

	Monitoring agencies			**Data collection mode**		
	National	*State*	*District*	*Field*	*Satellite*	*Ground based*
Meteorology						
Delay in onset of monsoon	W	W	D	D	Yes	Yes
Dry spell during sowing	W	W	D	D	Yes	
Dry spell during critical crop-growth periods	W	W	D	D	Yes	Yes
Hydrological						
Water availability in reservoirs	W	W	D	D	Yes	Yes (Volume)
Water availability in tanks/lakes	F	F	F	W	Yes	Yes (level)
Stream flow	F	F	F	W	-	Yes
Ground water level	S	S	S	S	-	Yes
Soil moisture deficit	F	F	F	F	Yes	Yes
Agriculture						
Delay in sowing	W	W	W	W	Yes	Yes
Sown area	W	W	W	W	Yes	Yes
Crop vigour	F	F	F	F	Yes	Yes
Change in cropping pattern	W	W	W	W‘	Yes	Yes
Supply and demand of agriculture input	W	W	W	W		

W – Weekly; **D** – Daily; **F** – Fortnight observation

Integrated spatial data base generated by incorporating information from various ground and temporal resolution could be effectively used in the drought situation vulnerable situations. Spatial information base thus created is the core knowledge engineering base for the management information system, expert system, knowledge base engineering and artificial intelligence studies.

References

Agterberg, F.P. (1974). Geomathematics. Elsevier, Amsterdam, pp. 596.

Crombley, R.G. (1984). Principal axis simplification. *Computers and Geosciences*, **18(8)**, pp. 1003-1012.

ESRI (1997a). ArcView Internet Map Server. Redlands, California, Environmental Systems Research Institute Inc.

ESRI (1997b). ArcView 3D Analyst. Redlands, California, Environmental Systems Research Institute Inc.

Huang, B., Jiang, B. and Li, H. (2001). An integration of GIS virtual reality and the Internet for visualization analysis and exploration of spatial data. *International Journal Geographical Information Science*, **15**, pp. 439-456.

Isaac, E.H. and Srivastava, R.M. (1989). Applied Geo-statistics. Oxford University Press, New York-Oxford, 561 pp.

Kraak, M.J. and Ormlering, F.J. (1996). Cartography, visualization of spatial data. Harrow, London.

McCullah, M.J. (1988). Terrain and surface modelling systems, theory and practice, *Photogrammetric Record*, **12,** pp. 747-779.

Raper, J. (2000). Multidimensional Information Science. Taylor and Francis, London.

Wilhite, D.A. (1996). A methodology for drought preparedness. *Natural Hazards*, **13,** pp. 229-252.

Further Reading

Bonham-Carter, G.F. (1994). Geographic information systems for geoscientists – modeling with GIS. Pergamon, 398 pp.

Fabbri, A.G. (1984). Image processing of Geologic Data. Von Nostrand Reinhold, New York, pp. 244.

Singhal, S. and Zyada, M. (1999). Networked virtual environments: Design and implementation. ACM Press.

Satti, S.R. and Jacobs, J.M. (2004). A GIS-based model to estimate the regionally distributed drought demand. *Agricultural Water Management*, **66**, pp. 1-13.

8

Vulnerability Assessment

Drought is usually declared based on the assessment of the current standing crop situation, relative to the normal condition. The drought is also declared if the following criteria are satisfied: (1) Steep reduction in area sown and also heavy damage to standing crops. (2) Considerable fall in extent of grain and fodder supply with abnormal increase in prices. (3) A trend of falling current agriculture and non-agricultural wages as compared with normal times. (4) Extent of unemployment position with reference to agricultural operation and on-going works of government, local bodies and big employers and (5) Unusual movement of labour in search of employment. Drought assessment processes and methods followed by various governments, vulnerability and risk assessment methods are highlighted in this chapter.

8.1 Drought Assessment

Indian states have managed drought primarily through short-term response-oriented processes (i.e., over days, weeks, months) focussed on minimizing emergencies and facilitating access to federal disaster relief programmes. An overview of the programmes of the countries and Indian states are given here. The Famine Commissions appointed by the British Government in India did suggest some measures like expansion of irrigation and railways, grant of loans etc. These measures were intended to provide immediate need to the distressed population and did not have the long-term perspective for improving the conditions in the chronically drought affected areas. The First and Second five year plans of India emphasised that as over a considerable area agriculture depended largely upon rainfall, the problems of dry land farming had to be given more attention than before. Conservation of soil and moisture by reducing the rate of run off, control of evaporation through soil mulches etc. are found useful for ensuring a good crop in bad years. There was a real awakening at the national level and the importance of evolving a long-term strategy for development of drought prone areas. Rural Works Programme was initiated during 1970-71 in 54 districts (along with some contiguous areas of another 18 districts) in 13 states which were identified as chronically affected by drought with the primary objectives of employment generation so as to mitigate the effects of drought.

The Irrigation Commission of India (1972) examined the problems of drought prone areas and envisaged the following criteria generally adopted by the states for determining drought prone areas: (i) meteorological data; (ii) revenue remission; (iii) frequency of famine and scarcity; and (iv) availability of irrigation facilities. It is suggested that the drought is the result of an imbalance between the soil moisture and evapotranspiration needs of an area over a fairly long period. The basic characteristic is a steady rise in temperature, in addition to the absence, or the severe deficiency, of rainfall over a fairly long period. The key role is played by rainfall and the crucial variables are its distribution, its variability and its capacity to meet evapotranspiration needs. All the identified regions were not equally vulnerable to crop failure. Protective irrigation was developed to stabilise agriculture. The minimum criterion for identifying areas susceptible to drought is that the probability of critical rainfall shortage should be 20% and that there should be an adverse water balance. Irrigation Commission had concluded that the *water balance technique* seems to be the logical approach for the objective of drought prone area delineation. This approach takes into account precipitation, evapotranspiration and soil moisture storage and attempts to arrive at a balance between water income and water loss.

The areas that are chronically drought prone were based on (i) incidence of rainfall over a period of time; (ii) extent of irrigated area in the district; (iii) environmental conditions like proximity to the irrigated tracts providing better employment; (iv) availability of other avenues of employment in the same area; (v) existence of schemes amenable to long-term economic development and lastly; and (vi) chronic liability of drought. Government of India has selected 54 districts in 13 states along with continguous areas in another 18 districts for the drought prone areas programme (DPAP) effective from 1973. They were divided into three categories: (i) Seven districts having extreme degree of aridity (Western Rajasthan and partly Haryana and Gujarat). (ii) Twenty districts semi-arid in character having annual rainfall between 15 and 30 inches. (iii) Areas being sub-moist. On the basis of rainfall, districts range from arid to sub-humid rainfall zones: rainfall upto 375 mm (arid); rainfall ranging from 375 to 750 mm (semi-arid); rainfall ranging from 750 to 1125 mm (sub-humid areas); and rainfall above 1125 mm. The drought prone areas, as at present identified by the Government of India, lie not only in the arid and semi-arid areas of the country but also in the sub-humid areas.

The main objectives of this programme were: reducing the severity of the impact of drought; stabilising the income of the people, particularly weaker sections of the society; and restoration of ecological balance. The important components of the programme are: development and management of water resources; soil and moisture conservation measures; afforestation, with special emphasis on social forestry and farm forestry; development of pasture lands and range management in conjunction with development of sheep husbandry; livestock development and dairy development; restructuring of cropping pattern and changes in agronomic practices; and development of subsidiary occupations.

Rainfall is highly variant in the semi-arid and arid regions and the temperatures are high, the evapotranspiration trends of the various types of crops are very relevant in planning a suitable cultivation programme. Generally, moisture stress in some part or the other of the growing period of the major crop of the area would be felt. The strategy would be to see that, during the crucial growth periods of a crop, there is sufficient moisture in the soil to support evapotranspiration requirements. A synoptic definition that a Block (group of revenue villages) can be defined as drought affected if the pattern and quantum of rain precipitation, during the main crop season of the area, makes the traditional cultivation of the main crop of the area hazardous in three years or more out of every 10 years.

Indian Famine Code (1950) contemplated that, apart from the failure of rain, certain symptoms demand attention such as warnings of possible distress: contraction of credits, restlessness indicated by an increase of crime, unusual movements of flocks and herds of cattle in search of pasturage, unusual migration of people, rapid rise in prices of common foodstuffs, great decrease in travelling by rail and attendance at festivals, abnormal unemployment, abnormal variations in the consumption of alcoholic liquor and abnormal sale due to riots for gold, silver and jewels at inadequate prices, falling prices of meat, cattle deaths and diseases and starvation deaths. Indian National Commission on Agriculture (1976) has classified drought into: *Meteorological drought* – normal precipitation below 25%, *Hydrological drought* – prolonged meteorological drought and drying of reservoirs, lakes, streams and rivers, cessation of spring flows and fall in groundwater levels, and *Agriculture drought* – depletion of soil moisture during growing season to support healthy crop leading to stress. *Hanumantharao Committee* (1994) has considered the percentage of area irrigated at district and block levels in different agro climatic zones as the main criteria for drought prone area. They have found 1173 blocks in 185 districts of 13 states – 120 Mha as drought prone. *Parthasarathy Committee* (2005) re-looked into various criteria for drought proneness and suggested that rainfall and irrigation support, historic NDVI from high resolution data and integration of these two methods for composite drought prone index are considered. As the drought is considered as state subject, the criteria for drought declaration followed by different states vary with unit area and criteria e.g., mandal level information on rainfall, crop sown area, yield reduction and dry spells by Andhra Pradesh; taluk level rainfall and dry weeks by Karnataka; village-wise paisewari system, yield loss 100 point scale by Maharashtra; block level rainfall and crop assessment by Orissa; yield loss criteria by Rajasthan, UP and J&K. Drought declaration at the state governmental level is completed in the month of September/ October. Memorandum of scarcity and verification by Central Government is completed prior to CCIF.

The Annawari procedure of estimating losses is used in Gujarat. It allows losses to be assessed in terms of scores (1 to 12 scores). It is assessed in each revenue village by Annawari committee which includes chairperson (a circle inspector or extension officer or Gram Sewak) and members (Talati Sarpanch, chairperson of cooperative society and a farmers' representative).* The committee estimates yield from three plots representing good, medium and poor crop conditions in a village by actual harvesting. The Annawari is calculated as:

Annawari score = (12 × observed yield)/(Standard yield of the villages)

The score less than 4 is considered to be the indication of a severe drought, while 4-6 moderate. This score is published by the Mamlatdar and invites objections if any from the villages within 15 days. After the objection registration period, the score is summarized for individual revenue village reporting to sub-divisional magistrate to district collector for evaluation and finalization. In Maharashtra, a similar system is called the Paisewari system. It operates on a scale of 1 to 100 scores and if a village gets less than 50 scores, it is declared as drought affected.

Andhra Pradesh government uses the following criteria for declaring drought: (1) Deficiency of rainfall (deficiency of rainfall of 25% and above in mandals where the annual rainfall is more than 1000 mm, 20% and above, where the annual rainfall is 750-1000 mm, 15% and above where the annual rainfall is less than 750 mm). (2) Compression/reduction in the cropped area of 50% and above under all principal crops. (3) Normal reduction in crop yields of 50% and above in comparison with average yields of preceding five years. (4) Dry spell and its impact on crops. Further, they also prioritize the mandals for drought mitigation activity based on average rainfall, coefficient of variation of rainfall, meteorological drought frequency,

---

* Revenue village, Taluk, district and state – representation of villages considered by Revenue Department.

Talati, Sarpanch, Gram Sewak – persons appointed by Government for Welfare of Villages in India.

Annawari/Paisewari – units of crop growth failure. Based on this parameter crop revenue collection is discounted/deferred.

hydrological drought frequency, agricultural drought frequency, groundwater status, feed and fodder availability, percent irrigated area (kharif and rabi), percent habitations fully covered under water supply and drought severity (agriculture). *Rajasthan* government uses the following criteria in drought declaration: the nature of the principal crops grown normally whether cash or food crops and their relative extent; the estimate of crops in the area with the actual damage of crop in percentage during the two preceding years; the nature and condition of population and break-up of marginal farmers, small farmers and families below poverty line; the extent of grain and fodder supply, with their normal and prevailing prices; the state of trade and the progress of exports and imports of food-grains and fodder; the trend of current agricultural and non-agricultural wages as compared with normal times; the opportunities of employment available on agricultural operations and works started by government, local bodies and industrial sector; unusual movement of labour in search of employment; and any other facts which indicate signs of distress.

Indian Meteorological Department delineates drought situation on sub-division level since 1875. A year is considered to be a drought year, in case the area affected by moderate and severe drought, either individually or together, is 20-40% of the total area of the country and seasonal rainfall deficiency during south-west monsoon season for the country as a whole is at least 10% or more. When the spatial coverage of drought is more than 40% it will be called as all-India severe drought year. Breaks in the monsoon rains can be of different durations, such as shorter duration like 5 to 10 days may not be of serious concern. But prolonged breaks of more than two weeks can create plant water stress leading to low productivity of crops. Application of meteorological information in terms of the frequency and probability of these breaks can be made to select a combination of crops of different durations in such a way that there is a time lag in the occurrence of their growth for appropriate inter-cropping systems. An *absolute drought* begins when at least 15 consecutive days have gone by with less than 0.25 mm of rainfall on all days (British Meteorological Office). Drought occurs when an area records rainfall deficiency of more than 25% during SW monsoon season (IMD).

Drought warnings, watches and advisories are intended to reduce the risk based on (1) normal levels of precipitation and/or (2) groundwater levels within the "normal" range. Therefore, groundwater levels within the normal range can include situation when groundwater levels are less than an average condition. The precipitation measures are: (1) three months of precipitation that are cumulatively above normal, and (2) long-term cumulative precipitation above normal. The period for long-term cumulative precipitation will range from 4 to 12 months depending on the time of year. Precipitation falling during the fall and spring are ideal for groundwater recharge. Parameters that are considered in fulfilling the administrative declaration of drought (agricultural losses) vary with state to state in countries. State-level drought assessment committee/drought watch group emphasise on the following parameters and frequency of measurement. Crop status with reference to productivity (before September/October) from revenue villages (basic unit of revenue department) is collected and verified by representatives of people, revenue officials (village level, block or tehsil/mandal), district collectors, Principal Secretary of states and sent to the drought assessment committee. This committee physically verifies and recommends to the National Calamity Crisis Management group for release of funds for people's welfare.

Government of India and state governments have the following programmes in minimizing the impact of drought on the people. They are: *Risk financing* – Crop Insurance; Calamity Relief Fund; National Calamity Contingency Fund; *Drought proofing* - Irrigation schemes; Drought Prone Areas Programme (DPAP); Joint Forest Management/Community Forest Management; Water Harvesting schemes; Micro-irrigation projects; State-wide irrigation development; Andhra Pradesh Rural Livelihood Project (APRLP); Watershed Development Programme; Integrated Wastelands Development Programme (IWDP); Rural Infrastructure Development Programme; Jawahar Gram Samridhi Yojna (JGSY); Sampoorna Grameen Rozgar Yojana (SGRY); *Employment generation* – Self-employment programmes on income generation; Employment Generation mission; Women Self Help Groups; Food for Work Programmes (FFW); Chief Minister's Empowerment of Youth (CMEY) programme; Employment Assurance Scheme (EAS). A common information database for the entire country will facilitate a more consistent approach to the drought declaration process through the use of a common template and language for describing drought in terms of probabilities; set of declaration criteria and process for the subjective "on ground" assessment of drought impacts.

However, the said administrative codes and manuals of different states did not visualize or fail to address the unprecedented manifestations of drought and constraints like: (a) The rainfall could fall in the following situations and not addressed are: *Situation 1* – Monsoon onset normal; crops sown and investment made; sudden withdrawal of monsoon; drying of crops and vegetation. *Situation 2* – Monsoon onset normal; crops sown and investment made; sudden withdrawal of monsoon and recovery after short spell; drying of crops and vegetation salvaged. *Situation 3* – Monsoon delayed; scanty rainfall in July; crops could not be sown and *Situation 4* – Monsoon onset very late; growing period curtailed; contingency resources not adequate. (b) Crop cutting survey estimates the losses by the state governments for declaration of drought. They have to wait till the crop is matured. If the crop sown is delayed to onset of rains, surveys become redundant. Hence, some states were requesting the drought committees for eye estimation or other

Multi-level drought monitoring agencies and frequency

	Monitoring agencies			
	National	*State*	*District*	*Field*
Meteorology				
Delay in onset of monsoon	W	W	D	D
Dry spell during sowing	W	W	D	D
Dry spell during critical crop-growth periods	W	W	D	D
Hydrological				
Water availability in reservoirs	W	W	D	D
Water availability in tanks/lakes	F	F	F	W
Stream flow	F	F	F	W
Groundwater level	S	S	S	S
Soil moisture deficit	F	F	F	F
Agriculture				
Delay in sowing	W	W	W	W
Sown area	W	W	W	W
Crop vigour	F	F	F	F
Change in cropping pattern	W	W	W	W
Supply and demand of agriculture input	W	W	W	W
Crop security				
Demand and supply of agriculture inputs	W	W	D	D
Emergency seed production programme	F	F	F	F
Water budgeting	F	F	F	F
Demand and supply of power and diesel	W	W	W	D
Food Security				
Distribution of food through PDS	W	W	W	W
Prices of essential commodities	W	W	W	W
Number of relief works	F	W	D	D
Number of people on relief works	F	W	D	D
Rural employment programme	F	W	W	W
Wage levels	F	F	W	W
Migration of people	F	F	W	W
Nutrition Security				
No. Integrated Child Development Service Centres (ICDS)	W	W	W	W
Number of people served ICDS	W	W	W	W
Number of people on mid-day meals programme	W	W	W	W
Supplementary nutrition programme	W	W	W	W
Health				
Waterborne disease	W	W	W	W
Malnutrition	W	W	W	W
Drinking water	W	W	W	W
Drilling rig movement	W	W	W	W
Social security				
Old age pension	W	W	W	W
Gratuitous relief	W	W	W	W
Livestock security				
Fodder prices	W	W	W	W
Fodder distribution through depot	W	W	W	W

W – Weekly; **D** – Daily**;** **F** – Fortnight methods of estimation. (c) Losses suffered by biodiversity, livestock fertility, orchards, perennial crops and plantations extending over years are not adequately included in the processes. (d) Monitoring of common property resources like fishery, forestry, groundwater and biodiversity are inadequately integrated into the drought proofing process. (e) Irrigated areas in a drought year also suffer losses due to excessive consumption of energy, diesel and ground water which is not monitored properly and accounted for in the estimation of losses. (f) Excessive depletion of groundwater resources during drought years and externalities of their recharging costs are inadequately analyzed.

Most of the governments also follow similar criteria in providing assistance to people in their fight against water stress as that of India. A synopsis of the practices is given below.

Australia

Drought is a normal feature of Australia's natural, economic and social environments. Climate-sensitive industries and enterprises have learned to manage drought risk along with others. The majority of Australia falls under arid and semi-arid regions, where occurrence of drought is a recurring feature of the island. It is found that many of the severe and widespread droughts are associated with El Nino events. Rainfall monitoring was the dominant factor in determining the success or failure of the growing season. Areas with rainfall accumulations below the 10th or 5th percentile for periods of three months or more are referred to as being seriously or severely in deficit. Although an extended period of rainfall deficiency in any area is virtually a prerequisite for drought. The formal declaration of a drought is a more complex issue.

Australian government adopts a policy of Drought Exceptional Circumstances for intervention based on: (1) Meteorological conditions; (2) Agronomic and stock conditions; (3) Water supplies; (4) Environmental impacts; (5) Farm income levels; and (6) Spatial scale of the event. However, the criteria for *Exceptional Circumstances* are: (1) The event must be both rare (occurs once in every 20-25 years) and severe (significant scale – measured by the number of farm businesses affected, sector impacts, size of the area affected, and overall value of lost production). (2) The effects of the event must result in a severe downturn in farm income over a prolonged period. (3) The event must not be predictable or manageable through normal risk management strategies available to farmers, or be part of a process of structural adjustment. Australia has identified the criteria for exceptional circumstances as *a rare event* that occurs once in every 20 to 25 years. It is expected to affect significant sections of farmers, industries and business. Hence, application for assistance needs to provide evidence of the status at his place/farm. It has had sustained and severe adverse affect on the income levels, a description of meteorological, agronomics and environmental conditions arising from the event, location of the affected and the timing and duration; impacts on crop production, stock returns, water supplies and farm viability, scale of the impact, the value of products etc. The following modes of assistances are offered:

Exceptional Circumstances Interest Rate Subsidy – Farmers Assistance (90% contribution) provides interest rate subsidies to farm enterprises that are viable in the long term, but are in financial difficulties; *Small Business* (90% contribution) provides business support (Interest Rate Subsidies) to small businesses that are viable in the long term, but are in financial difficulties due to Exceptional Circumstances (EC) events. *Exceptional Circumstances Relief Payment (ECRP)* – (Farmers) assists farm families in EC declared areas that are experiencing difficulties meeting basic living expenses. *Small Business* – assists small business families who are experiencing difficulties meeting basic family expenses. *Health Care Cards* – for individuals or family to obtain health concessions such as cheaper prescriptions and other health, household, educational, recreational and transport services. *Interim Income Support (IIS)* (Farmers) – assists eligible farm families in areas to have established a prima facie case for EC assistance or who are located in an Interim Assistance Area (ending September 2008). When the government makes a full EC declaration for a prima facie area IIS is replaced by the Exceptional Circumstances Relief Payment (ECRP). *Small Business* – assists eligible small business families in, or dependent on, areas declared by the Australian government.

Country Women's Association (CWA) Emergency Drought Aid Fund 2006-2008 provides emergency aid grants to drought affected rural families and communities to meet the immediate household needs as vouchers or through direct payment of bills. *Professional Advice and Planning Grant* enables eligible farm enterprises to access professional business and financial advice and planning assistance for the purpose of developing written business plans incorporating drought and risk management strategies. *Earlier access to funds for FMD holders* allows primary producers an early access to their FMDs, without losing the taxation benefits. *Rural Financial Counselling Service Programme* – provides grants to support the provision of a free and impartial rural financial counselling service to primary producers, fishers and small rural businesses in financial difficulty. Rural financial counsellors are not able to provide financial advice, personal or emotional counselling or succession planning. *Declared Drought Area Incentives* – drought in a region has a direct effect on the training and employment opportunities of that region. Australian Apprenticeships Incentives Programme encourages primary producers to continue to offer skills development and employment. *Access to Job Search Support* for redundant rural workers in drought-affected areas gives employees who have been made redundant or are facing redundancy access to Job Search Support services. *Early access to Intensive Support* (job search training) for rural workers in drought-affected areas provides individuals who have been laid off as a result of the drought.

Drought Force Work for the dole programme provide assistance to communities dealing with drought. It provides people who are laid off as a result of the drought and other suitably skilled unemployed people from the local area an opportunity to participate in drought mitigation activities on drought-affected properties or to work on community projects in drought-affected communities. *Flexible Arrangements for Newstart* allowance and other benefits for people unemployed due to drought measure is designed to help unemployed people in drought affected areas get onto Newstart Allowance and other payments quickly. Social and emotional counselling for drought affected families under the *Family Relationship Services Programme* (FRSP) will fund organisations to provide vital face to face counselling and other support measures related to the drought to improve access to personal counselling services in rural regions. *Local Answers – Strengthening Drought Affected Communities* will fund projects specifically in areas that are Exceptional Circumstances declared or areas that can demonstrate significant hardship as a result of the drought.

Tax Office – help available for drought affected areas; and taxation measures for drought affected farmers help taxpayers affected by the drought by giving them more time to lodge and pay their income tax and activity statements without penalty; allowing additional time to pay tax debts without incurring charges; arranging for tax debts to be paid in instalments; remitting penalties or interest that may have been imposed; and fast tracking refunds. Taxation measures relate to: farm management deposits; profit from forced disposal or death of livestock; double wool clips; insurance recoveries; water facilities; and land care operations. Transport subsidies are: 100% subsidy for transporting donated fodder and a 50% subsidy on the cost of transporting fodder, including for bees, stock water, including for bees, domestic water; stock to and from agistment; stock to sale or slaughter. *Drought Carry-On Finance* assists in providing business carry-on requirements to primary producers. *Drought Preparedness* provides research, planning and development information to primary producers through a range of mechanisms to promote primary producer self-reliance, for example: monthly climate forecasts; *Rural Risk Strategies facilitates*; Managing for Climate and Weather; and Risk Management workshops. *Drought Recovery Scheme* assists primary producers recover from drought and re-establish their enterprises. *Drought Relief Assistance Scheme* provides freight subsidy assistance for transport of fodder, stock drinking water, livestock returning from agistment and restocking post drought. *Electricity Tariff Relief* allows waiving of fixed charge components and deferral of payment for pumping of irrigation water. *Mortgage*

Stamp Duty Relief provides mortgage stamp duty relief for farmers needing to extend finance as a result of the drought. *Financial Mediation* makes available financial mediation services for primary producers who need assistance negotiating with their bank. *Drought tolerance traits for wheat and lucerne* – Develop rapid screening methodologies for drought tolerance in wheat, and identify traits conferring drought tolerance in lucerne genotypes at establishment and in existing stands. Rebate on purchase of Water Tanks by eligible customers of the *Grampians Wimmera Mallee Water Authority (GWMW)* helps to purchase water tanks to enable carting to their properties. The Victorian government is providing a partial rebate on the purchase of these tanks. *Assistance for rural water users* provide assistance with the fixed water supply charges of rural water users receiving very low water allocations since 2006-07. *Catchment Management Authority (CMA) Drought Employment Programme 2007-08* provides an income for drought-affected rural Victorians and helps local communities by maintaining and restoring natural assets on public and private land.

New Zealand

Drought relief consideration for farmers was triggered when rainfall at representative climate stations in a drought-affected area, for a consecutive three-month period, was at a one in 20-year low in New Zealand. This measure was often further qualified by the additional condition that total days of soil moisture deficit, based on a daily water balance calculation, were correspondingly high. Economic consequences of drought were measured in terms of: (1) loss of production and gross farm income (individual and regional); (2) changes in expenditure patterns and run down in savings; (3) GDP losses; and (4) environmental consequences.

United States of America

The ‘trigger points’ for drought assessment (National Drought Policy Commission, USDA, 2000) need to be both *supply-type*, reflecting moisture deficiencies caused by acts of nature (lack of rain, excessive temperatures), as well as *demand-type*, reflecting drought impacts. The scale of the information should be representative of the area experiencing drought and comprehensive enough to adequately examine corresponding impacts. The drought indicator information needs to represent: *Environmental information* – (1) Precipitation-based areas most susceptible to drought, and characterizes drought patterns over time in drought-prone areas; (2) Water supply sources (both surface and ground water) and proximity to water sources in a different hydrological basin to where a drought occurs; (3) Impacts of soil loss (sheet erosion) and sediment deposition due to heavy rain following dry periods; (4) Impacts on surface and ground water, from soil moisture to lakes and wetlands, including both quantity and quality of water; (5) Effects on air (such as dust storms); and (6) Effects on wild life and plants – impact on habitats, diversity, and stress on species. *Economic information* – (1) Understanding economic linkages and trends and the impact on rural communities and on families; and (2) Other economic factors – e.g. awareness programme, drought recovery loan schemes, and insurance. *Social information* – (1) Public health and safety such as health risks due to water shortages or contamination in dry seasons, mental and physical stress brought on by the situation, and the physical dangers posed by fires; (2) Individuals' perceptions of drought – and differing interpretations of drought characteristics may produce different attitudes and perceptions of how to deal with drought; (3) Acknowledging diversity – wide range in the way drought affects people, due to the diversity in social, cultural and economic circumstances; (4) Government/NGO interactions – dialogue is important to determine best policy implementations for drought preparedness and relief; and (5) Political or government perspectives – avoidance of conflicting objectives in the management of economic sectors, where they make effective drought planning more difficult.

The drought indices need to highlight – (1) *Accumulated deficit* based on the occurrences of water deficiency, rather than just the departure from climatological mean. (2) *Time step* – Daily units of time were essential, because a water deficit could be overcome by just a day's rainfall. (3) *Water storage term* characterizes both soil moisture and other water resource (e.g. lakes, ground water) storage as separate features. (4) *Time dependent reduction function* in accounting for daily water resource depletion through runoff, evapotranspiration and other factors, particularly to evaluate the residual resource of rainfall that had occurred some months previously. (5) *Modelled or estimated data* are the *over-simplification of data*, hence it is better to use measured parameters only, such as precipitation. (6) *Lack of other information* – Drought indices failed to provide good information on the duration of drought, how much deficit of water had occurred, when the drought was likely to end, and how much rainfall was needed to return to normal conditions.

The currently used drought indices of United States of America**,** were not precise enough to detect the onset, end, and accumulated stress of drought. The drought studies need to focus on – (1) *Causes* directed at understanding atmospheric processes that lead to drought; (2) *Frequency and severity* directed at characterizing the probability of drought events of various magnitudes; (3) *Impacts* directed at quantifying the costs and losses associated with drought, including economic, social and environmental consequences, which may be direct or indirect; and (4) *Responses* directed at preparedness and mitigation strategies, and focussing on means of impact reduction.

Drought declarations and assistance are provided by USDA Farm Service Agency (FSA) and Small Business Administration (SBA). There have been no Presidential disaster declarations for drought, except for those related to wild land fires. The declarations at the Federal level have been from the Secretary of Agriculture and are referred to as Natural Disaster Determinations (NDD). NDDs allow assistance programmes, such as the low-interest FSA Emergency Loans to eligible producers, and assistance through the Crop Disaster Program, Livestock Compensation Program, and Livestock Indemnity Program.

USDA co-ordinates and supports the following drought assistance programs: *Emergency Food Assistance Program* - USDA provides emergency food assistance to states that are in crisis. It purchases, processes, and packages the food, then ships it to the individual states. *Emergency Food Safety Information* – Disasters can jeopardize the safety of food due to unfavourable conditions and information is provided on how to determine if food is safe and how to keep it safe in cases of emergency. This helps to minimize the risk of food-borne illness in emergency situations. *Federal Disaster Assistance Information* helps to keep the public prepared when disaster strikes with safety alerts, preparedness lists, and disaster prevention information. *Food Aid Programs* help provide the U.S. agricultural commodities that feed millions of hungry people in needy countries through its direct donations and concession programmes. *Emergency Loan Assistance* provides emergency loans to help producers recover from losses due to natural disasters or quarantine. *Emergency Watershed Protection Program* safeguards lives and property from floods, droughts, and the erosion on any watershed, when natural occurrences cause a sudden impairment of the watershed. *Non-insured Crop Disaster Assistanc Program* offers financial assistance to producers of non-insurable crops when low yields, loss of inventory, or prevented planting occur due to natural disasters. *Crop Disaster Program Facts* offer facts and information on crop disaster as a part of its Crop Disaster Assistance Program. *Crop Insurance Policies* offers crop insurance policies as a risk management option for agricultural producers. *Rural Development Disaster Assistance* in rural areas offers financial assistance (loans, grants, etc.) to help minimize financial hardship.

Agricultural Assistance Act of 2003 provides assistance to producers who have suffered losses due to weather-related disasters, or other emergency conditions. *Tree Assistance Program (TAP)* provides financial assistance to qualifying orchardists to replace eligible trees, bushes, and vines damaged by natural disasters. *Defending Against Drought Tips* provides ideas on water, land, and crop management for people to consider while creating their drought plan to protect farms and ranches. *National Drought Mitigation Center* helps people and institutions implement measures to societal vulnerability to drought. It stresses preparation and risk management rather than crisis management. National Water and Climate Center (USDA) collects information on spatial snow, water, climate, and technology. Joint Agricultural Weather

Facility – The department collects global weather data and agricultural information to determine the impact of growing-season weather conditions on crop and livestock production prospects. *Wildlife Disease Protection Program* aims to reduce the risks of disease transmission from free ranging wildlife to animal agriculture. *Pest Detection Program* protects America's agricultural and ecological resources by ensuring the early detection of harmful or economically significant plant pest and weeds.

Programmes on drought management activities assess the *Monitoring of Hydrologic Conditions:* Continuous monitoring of hydrologic conditions is necessary to identify and track drought conditions. Actual measurements of precipitation, stream flow, lake levels, groundwater levels, and water use are all essential to understand and characterize drought. *Regulation of Water Appropriations:* Any appropriation of (surface or ground) water exceeding 10,000 gallons per day or 1,000,000 gallons per year requires a DNR water appropriation permit. Permit conditions define *withdrawal limits* and require conservation to avoid water use conflicts and provide for sustained use. *Surface water appropriations* are generally discouraged for irrigation because the highest demand for irrigation coincides with periods when surface water levels are low. These permits are subject to suspension during periods of specified low flow to help maintain in-stream flow and provide for higher priority water uses.

Resolution of Water Use Conflicts and Well Interference Problems – Water use conflicts arise when water demands exceed the reasonably available supply of surface or ground waters. Well interferences occur when a high capacity well intercepts water from a higher priority water user. Water use conflicts can be a long-term regional problem, while well interferences tend to be short-term and localized in extent. *Water Allocation Planning* – A water allocation plan is an agreement describing how the available water supply (the quantity in excess of resource protection levels) will be shared during times of shortage. *Emergency and Conservation Planning* – Public water suppliers serving more than 1000 people to have an approved emergency and conservation plan. These plans address procedures to be taken during periods of limited water supplies. *Hydropower Facility Relicensing* – Each facility must go through a relicensing process every 30-40 years. State resource agencies play a significant role in the relicensing process. It advocates run-of-river facility operation to minimize artificial fluctuations in river flows and avoid harmful impacts to aquatic habitat and other in-stream values. *Information and Technical Assistance* – Provides general advice and technical assistance to individuals and communities facing water supply emergencies, and provides general advice and information on water conservation techniques. *Water Supply Development* activities support water supply development by conducting groundwater investigations, monitoring stream flow, and providing information on water availability. The rules governing these permit programmes incorporate the principles of adequate water availability, safe yield, efficient use, and water conservation.

China

Since 1955, Beijing Climate Center uses Standardized Precipitation Index (SPI) in monitoring drought occurrence and development in China on 10-day basis. Results are published in China Drought Monitoring (CMA) Bulletin. Cl is a function of the last 30-day and 90-day SPI and the corresponding potential evapotranspiration. Based on Cl and soil moisture monitoring from an agricultural meteorological station network and remote sensing based monitoring from CMA's National Satellite Meteorological Center, a number of drought monitoring products are produced.

South Africa

South African Weather Services use SPI in alleviating the principal shortcomings, as it is based on the probability of rainfall for any time scale and can be used for various time scales. Neither the percentage of normal nor the decile-based drought indices can assist decision makers with the assessment of cumulative effect of reduced rainfall over various time periods. Republic of South Africa declares drought when the farming conditions, availability of natural and cultivable pastures, fodder production and water supplies in a specific area have deteriorated to the extent that natural agricultural resources and livestock are seriously affected. Monetary incentives/compensation packages such as rebate on transport of stock feed, contribution in maintenance of nucleus herd, stock reduction and grazing lease scheme were announced.

Portugal

Palmer Drought Severity Index is used in Portugal in characterizing drought. Calibration has been done to the specific climatic conditions of mainland Portland, prior to its utility.

Drought exposure is often defined geographically by assigning a spatially averaged value within political, landscape, and watershed boundaries. It is frequently expressed as the magnitude, spatial and temporal qualities, etc. of an extreme geophysical event. Dry land farming and free-range livestock operations, in contrast, rely on adequate rainfall for crop and range quality and thus can be highly sensitive to drought exposure. Adaptive capacity refers to the "ability of a system to adjust to perturbations and changes in variability or system states to moderate potential losses, to take advantage of opportunities, or to cope with consequences". The term "system" refers to a variety of geographic scales: household, community, landscape, region, nation, and global. It can also refer to spatially disaggregated systems such as economic sectors, cultural groups, governments, and biomass. In terms of drought planning, adaptive capacity refers to how effective a system is at mitigating the consequences of first-, second-, third-, etc. order impacts. Adaptations can be pro-active or reactive. Effective adaptation is contingent on sufficient capacity to adapt, which in turn requires a broadening of vulnerability analyses to examine other factors, including household dynamics, community cohesion and health, social change, political and economic institutions, land-use change, and ecological dynamics (Wilhite, 2000).

8.2 Vulnerability

Human and natural resource activities depending solely on rainfall and soil moisture, such as dry-land farming, ranching, and some environmental water uses are at *extreme risk* from drought. These activities can suffer discernible effects even with droughts of short duration. The water use activities that depend on stream flows such as direct flow irrigation, recreational water uses, aquatic, wetland and riparian environmental communities are also at *extreme risk*. Many urban and agricultural water users who rely on surface water reservoir supplies or on groundwater resources that are not dependent on high rates of aquifer recharge or adversely affected by concentrated levels of high pumping are at *moderate risk*. Depending on the objective and resource availability (data and information, natural and human, finance), it is classified into: *Rapid* (Summary and overview of data sources and information), *Intermediate* (detailing) and *Comprehensive* (in-depth analysis on smaller spatial scale). Meteorological and hydrological data networks are often inadequate in terms of density of stations for major climate and water supply parameters and missing data or inadequate length of record affects data quality and analytical results. Data sharing is inadequate between agencies and research institutions. Further, the forecasts are often unreliable on the seasonal time scale and lack specificity to be used in agriculture and other sectors. Drought indices are inadequate for detecting the early onset and end of drought. Drought monitoring systems need to be integrated with multiple climate, water and soil parameters and socio-economic parameters in characterizing the drought magnitude, spatial extent and potential impact.

Vulnerability expresses the degree of susceptibility to a hazard either as the result of varying exposure to the hazard or because of variations in the ability to cope with its impact. Vulnerability index was developed as a linear combination of set of standardized variables. They are scaled down to common numeric index and assumed to follow a normal distribution. Impact of marginal delay in monsoon and period of rainfall affect villages that depend heavily on them. Hence, vulnerability of the revenue villages is assessed, based on their sustainability to manage their natural resources in terms of: (1) Dependence intensity on type of water resources for irrigation and drinking water (irrespective of their supply problems), (2) Available capacity (storage system) to store rainfall and utilization, (3) Awareness of their demands and probable deficit under different rainfall conditions, (4) Conservation efforts (deficit irrigation/demand reduction) and alternate source supply identification and (5) Self rainfall and water level monitoring and preparedness and management, irrespective of their geographical location.

An effective assessment of drought vulnerability needs to include more dynamic elements, such as social processes of exposure and responses to natural disasters. Real world vulnerability should encompass some notations of the threat, exposure unit and consequences on different scales. Figure 8.1 shows the spheres of vulnerability that could be adopted for drought. The vulnerability mapping measures develop an index as linear combination of a set of standardized variables. Cutter (1996) proposes a "hazards of place" model and says that "vulnerability is the likelihood that an individual or group will be exposed to and adversely affected by a hazard".

Elements of vulnerability due to drought are: Who is vulnerable to what; External and internal elements; Exposure to threats; Sensitivity; Adaptive capacity; Combining quantitative and qualitative data; and participation. This is carried by: *Step 1:* Description – Location – geographic location, climatic

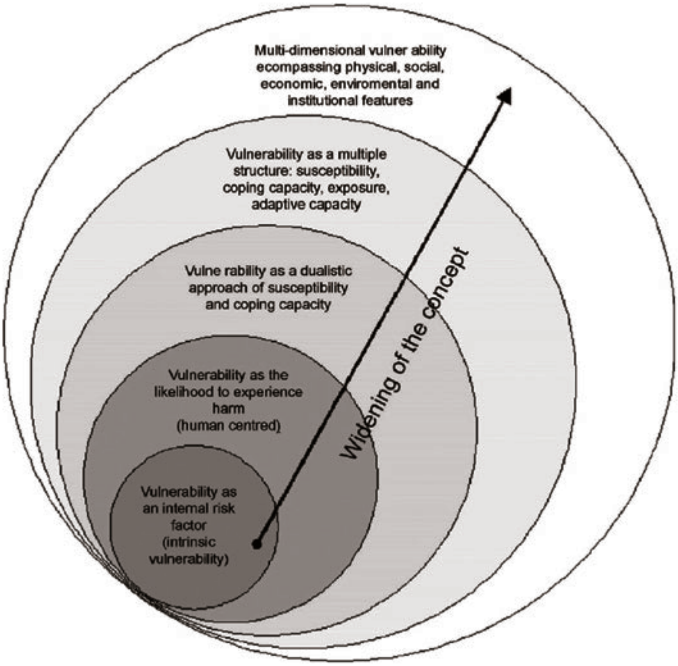


Fig. 8.1: The spheres of vulnerability (Birkmann, 2005).

zones; System elements – population, physical attributes (rivers, infrastructure, etc.); Current issues – management (plans) and public issues (resource conflicts); NAPA/vulnerability assessment team–members, skills; Supporting material – documents detailing other studies, data. *Step 2:* Scoping of threats – inventory of threats – climate hazards, economic crisis, institutional changes; Impacts of threats – significant historical events; Exposure units – who is exposed, at what scale, what is nature of exposure? *Step 3:* Scoping vulnerability – Major concerns – elicit from populations at risk and managers; Attributes of vulnerability – cluster concerns into major dimensions of vulnerability; Exposure matrix (livelihood sensitivity matrix) – exposure units and threats (assign sensitivity, scale 1-5); Comparison – identify importance of different factors. *Step 4:* Indicators – identify priorities (e.g. sectors) and scales of assessment (exposure units); Identify key indicators of vulnerability attributes that suit local needs (e.g. rainfall variability, income, malnutrition, access to water resources, main livelihood activity, housing type); Collect indicator data; Compile profiles of indicators from different case studies. *Step 5:* Reporting – description of area (relevant to assessment); Exposure – who is exposed to what; Vulnerability attributes – describe dimensions of vulnerability and choice of indicators; Present data on indicators; Synthesis and narratives (story according to vulnerable groups).

Water planning approach would help in understanding the vulnerability by incorporating: (1) introduce differential social and economic vulnerability to catchment planning models; (2) capture the dynamic element of vulnerable groups and their relationship to water resources and catchment or regional planning; (3) represent the multiple attributes of vulnerable groups and make the link to their ability to respond to stresses and threats; and (4) represent the decisions of actors (the managers and vulnerable groups) in the construction of adaptive systems (i.e., in the reduction of future vulnerability).

In *non-irrigated areas*, farms depend on the exploitation of shallow groundwater wells, and rainfall, making them more vulnerable to drought than irrigated farms. However, increased irrigation has depleted water resources and is likely to become an acute problem in the region. Therefore, although irrigation reduces dependence on rainfall, increased irrigation has reduced water resources to unsustainable levels in the region, depleting strategic reserves and thereby increasing water scarcity and vulnerability to drought. Figures 8.2 and 8.3 show the dependency of revenue villages on the surface and groundwater resources for irrigation purposes. It is implied as percentage of total irrigated area using river, lake and canal to gross irrigated area of the villages. Similarly total irrigated area using open dug wells, bore wells etc. to that of the gross cultivated area of the villages. Class intervals are made according to the utility pattern. This would help in the identification of measures for development purpose of the supply system on a watershed or river basis or canal command basis or control on the groundwater exploitation on aquifer system or landform basis.

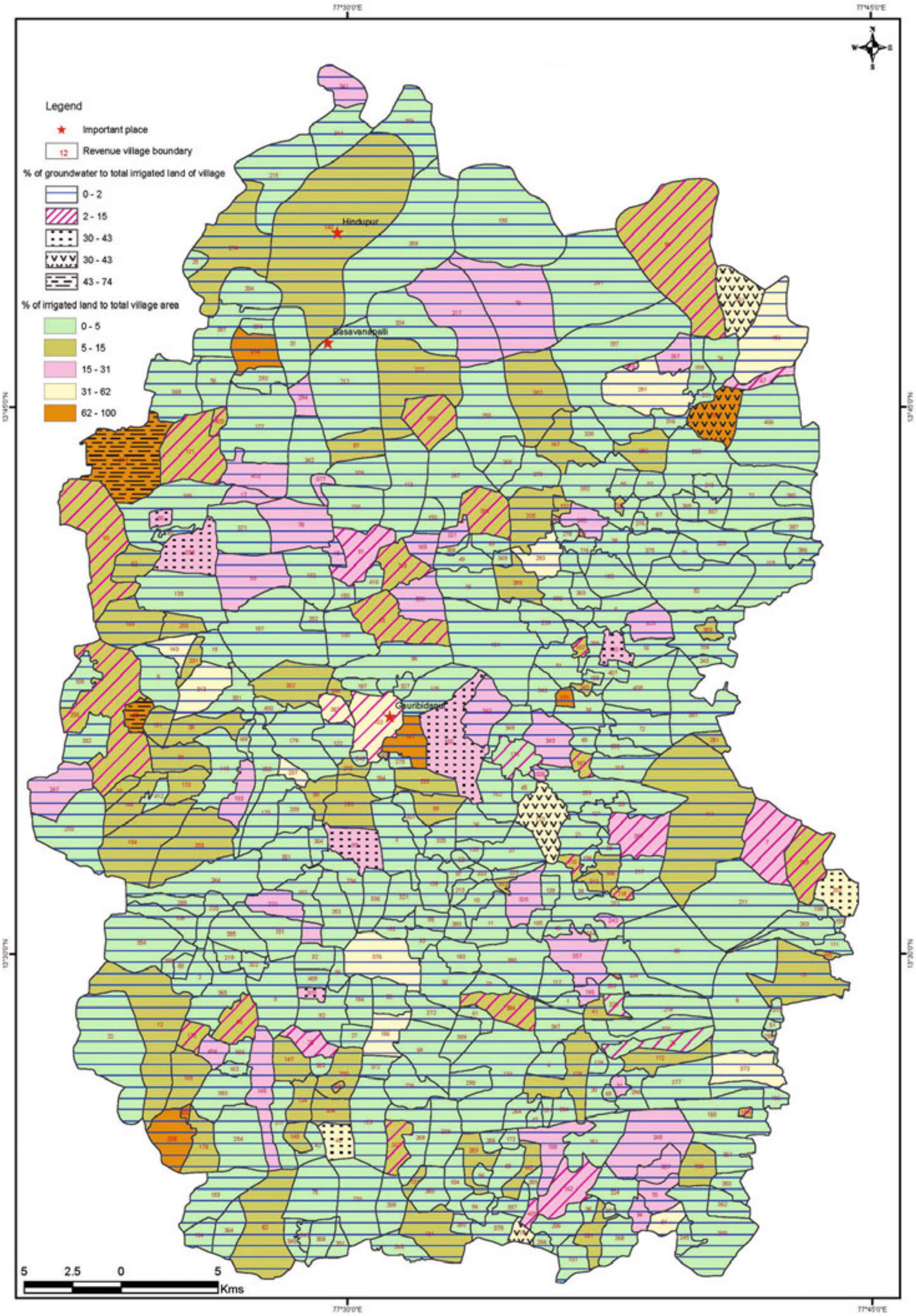


Fig. 8.2: Surface water dependency of revenue villages.
Source: Census of India (Karnataka), 2001

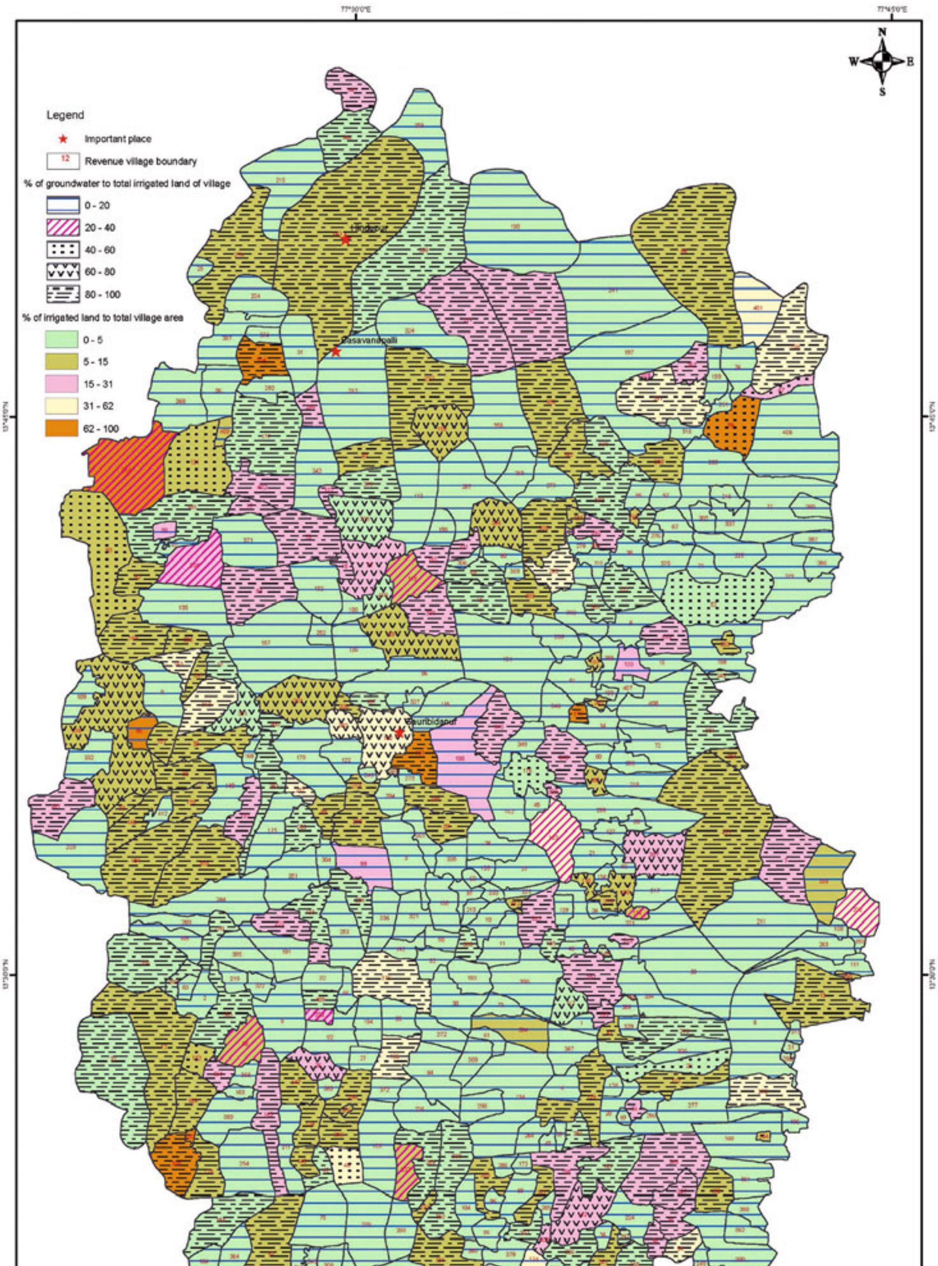


Fig. 8.3: Groundwater dependency of revenue villages.

Source: Census of India (Karnataka), 2001

Crop vulnerability to drought depends largely on local climate, soil conditions, seed variety, drought resistance of seed, timing of drought, temperatures and farming system. Certain crops are less able to adapt to higher temperatures and require more water and they are more susceptible to drought. *Climatic risk zoning* determines the potential suitability of specific crop for a given region and the probability of drought during the crop growing period. It is based on the factor that affects crop development, phonological stage that is susceptible, cropping aspect and availability of meteorological information. *Agriculture drought vulnerability* is a complex phenomenon that links meteorological drought and soil moisture deficits to impacts on crop and forage yields and livestock production. Extended periods of precipitation deficiency continue to result in significant impacts on agricultural production (Wilhite and Vanyarkho, 2000). Vulnerability to drought is dynamic, and is the result of land use and management, farm policies, and many other factors.

Summary of the findings of a survey on farmers' adaptation by drought affected communities conducted by Winrock International India, New Delhi, on behalf of the World Bank in five mandals of the Mahbubnagar district, Andhra Pradesh are: *Irrigation practices* – Increasing the number of tube-wells and with a decrease in the number of traditional tanks and open-wells, increase in the depth of the tube-wells between 200-300 ft (approximately 61-91 metres) to access lower ground water levels; *Cropping practices* – Decreasing the area cropped due to lack of water and labour where family members have migrated out of the district; Temporarily adapting crop cycle to suit the time of rainfall; Limited examples of changing to high yield crops, horticultural (sweet orange, mango, acid lime etc.) and mixed cropping which are promoted by government programmes; *Migration/labour* – Migration of members or whole families to outside the districts for livelihood, such as construction labour; sending children to work as labourers; working at lower wages to generate some income; *Financial* – Taking loans from money lenders (50-60% of total loans) or self-help groups where debts of farmers vary from Rs. 30,000 to Rs. 200,000 (70% is for agricultural inputs and 30% for marriages, health, house construction or renovation); pawning of household items and jewellery; the poorest people reduce expenditure on basic needs, leading to malnutrition and in extreme cases, starvation; sale of livestock at depressed prices due to lack of fodder or agricultural work for the livestock; *Extreme practices* – Suicide.

8.3 Vulnerability Analysis

Even though all types of droughts stem out from precipitation deficiency, it is not sufficient to rely solely on climate-related parameters in evaluating the severity and its impacts. Withdrawals exceeding 20% of renewable water supply has been used as an indicator of water stress in initiating water resource legislation and management (IPCC, 2001).

Ranking and Weightage

The influence of various exogenic and endogenic factors that are responsible in the water stress and related conditions varies with agro-climatic zones and local conditions. Table 8.1 shows the parameters that are used in drought vulnerability studies and mode of data collection. The qualitative classes require a ranking system by which each of the contributory factors can be quantified and weightage of individual factors can be assigned. The various available methods of weightage are: Blind weighing (relative importance is assigned based on personal experience), sighted weightage (ratings are improved by event analysis) and post-event weightage (type and magnitude of triggering events are considered). It is found that occurrence of event is directly or indirectly related to these factors. They were sub-divided into number of classes (minimum four or maximum five) based on the frequency distribution and dispersion of data. Individual factors were given a weightage, as observed from the reported events and their role in triggering. Significance of individual factors and their weightage was established by observation and analyses of the past events. Occurrence of an event is the resultant of these factors. A composite value for each class can be found by adding all the values. A cumulative risk equal or higher than that of reported event is taken as very high.

Weights assigned to each parameter reflect its importance in the event-occurrence, together with the rating for the individual classes that denotes the event intensity. The class intervals are derived from the observed event severity of the past and from the natural contributory nature. The weights and class intervals were derived from the past events. The various parameters of significance were grouped into: Frequency of events (historical), climate (time series of rainfall, rainfall fluctuation, evaporation, aridity), resource availability (vegetation cover, food-crop area, cash crop, water surface and ground water), demand (population density, growth, industry), distribution loss (surface storage, system efficiency) and sharing of resources (proximity to infra-structure facility) etc. Even though all these factors are inter-related, the weights of these factors were assigned based on the observed deficits.

In a tropical monsoon country like India, the formation of clouds, its movement towards Indian sub-continent, advancement through the continent and rain at appropriate geographical locations are important in deciding the pre-sowing agriculture practices and management of available surface water and groundwater extraction. Period of the *formation of clouds* (FC) with mean period observed during the past few decades or 100 years is important. It is grouped into four classes. *Arrival of monsoon* (AM) clouds at the southern portion of sub-continent is taken as the base line information in

Table 8.1: Drought indicative parameters

Chronical	*Monsoon*	*Weather*	*Water resources*	*Agriculture*	*Socio-economic*
Frequency of drought Reported Drought occurrence Annawari/Pasiawari declaration freuqnecy	Monsoon setting @ origin Monsoon arrival @ India Advancement of monsoon Commencement of sowing rain Normal monsoon rainfall (10 yrs)	Annual rainfall (100yrs) Monthly distribution (10 yrs) Weekly Rainfall (5 yrs) Un-seasonal rains if any (flowering stage) (10 yrs) Deviation in temperature Humidity Evapotranspiration rate variation	Dependency on surface water Conditions of storage & distribution system Reservoir/Lake level Distributary's canal dependency Canal command supply satisfaction index Dependency on Groundwater Aquifer type Ground water level (Min & Max) Ground water level fluctuation Intensity Tube/bore/ open dug well Abstraction – recharge efforts ratio Quality of water Population – source dependency Water demand – crop, Human & Livestock (measure RF) Supply deficiency Irrigated area/ Cultivable area	Stable crop/ cultivated area Cash crop + not suitable crops/ cultivated area Water intensive crop area Crop production deviation Soil-crop suitability	Un organized workers % of Farm workers Population – human Livestock Income level

calculating its arrival at individual sites/regions over the rest of the country. If the arrival is earlier than the anticipated date, initial rainfall could take place earlier than expected, that warrants commencement of pre-sowing activities. It is grouped into five classes with reference to mean. However, the sluggishness of movement due to atmospheric disturbances that are dynamic and global in nature could only be accounted for and not formalized. *Commencement of sowing rain* (CSR) – Reliability of occurrence of conditions suitable for sowing and identification of such specific periods are of considerable importance to agriculture. The planner considers the CSR to be early when the arrival of sowing rains is before 18 June, normal when it is between 18 and 24 June, late when CSR is between 24 and 30 June, and definitely late when the arrival is delayed beyond 30 June. The delayed dates of a region signifies the probability of an event. Hence, they are grouped into five categories of seven days interval.

Period of Difficulty (PD) (anticipated) was calculated from annual rainfall data of 100 years. Time series analysis of rainfall indicates the periods of low, normal and excess rainfall. This cyclic pattern (long-term) is used in evaluating the deficit, normal or excess monsoon rainfall. If the year under consideration falls in the deficit rainfall period, then it is assumed that the period of difficulty for the forthcoming period is very high. Five classes were made according to the historical events of the region. Moving average method is used in identifying the onset of exceptional drought conditions based on climate and pastoral conditions (Donnelly et al., 1998). The observed *Frequency of Events* (FE) during the past is the significant information, in ascertaining the forthcoming/expected drought event. It is observed that parts of Indian sub-continent undergo drought condition once in 1-2, 3-5, 5-7 or 9-10 years. This cyclic pattern of event occurrence is noticed for the past 200 years. The year under consideration, if it falls on the probable year of drought, then it is grouped as very high and low accordingly.

Distribution of monthly rainfall (MRF) within the year affects the desired soil moisture, crop yield etc. The monthly rainfall fluctuation within the past 10 years would indicate the anomaly. The major shift/fluctuation in the monthly rainfall pattern would lead to drought. It leads to the external irrigation facility needed for a crop during the monsoon period. The shift/untimely rainfall disturb the crop calendar. Unprecedented rainfall also leads to damage to the crop. Hence, fluctuation in the past ten years was considered. They were grouped into five categories. *Aridity Index* (ArI) indicates the dryness of the region. It considers the temperature and rainfall of the region. It has been grouped into four categories. *Palmer Drought Severity Index* (PDSI) indicates the actual and required rainfall for the region. It is one among the widely estimated indices. It takes into consideration rainfall, soil moisture etc. This has grouped into five categories. *Evaporation* (Eva), from the surface water bodies is an important factor in the conservation. This depends on the temperature, and humidity in a region. It is grouped into five classes.

Land vegetation cover is estimated using Normalized Difference in Vegetation Index (NDVI) from the satellite data (coarse and finer ground resolution) in understanding the healthiness of regional vegetation. It is found that higher the NDVI greener the surface and lower the NDVI degraded the surface. It is grouped into five classes. *Total crop area*_(TCr) in a village indicates the excess water demand during summer. The groundwater draft will be high during the rainfall deficit periods. Further, distribution of precious water amongst the crops needs to be worked out in saving the crop. Hence, the crop area in a revenue division was grouped into five categories based on its share within the village boundary. *Cash crops* (CaCr) such as sugarcane, banana etc. are water intensive in nature. The economic consideration drives the farmers to go for these crops. The stake of the cultivator is also high compared to dry crop cultivation. Ratio of the cash crop amidst the normal crop area indicates the race for water in region. This ratio has been grouped into five categories. The demand will be high from the high ratio villages and vice-versa. *Crop Moisture Index* (CMI) indicates the availability of soil moisture supply in the short term across major crop that is required for sustainability of crops. Meteorological approach is used to monitor week-to-week crop conditions. It responds rapidly to changing conditions. It is grouped into five classes.

Surface water storage (SWS) in the form of lake/pond is widely used in conservation of surface run-off. The water-spread area demarcated from the satellite images indicates the conservation practice of the region. The availability of such areas with reference to total area of investigation will indicate the existing practices and scope for improvement. Lesser the water surface area in reservoirs, higher the probability of water deficit. It is grouped into five classes. Physical *condition of the canals* (CC) and activities that lead to degraded conditions indicate the efficiency of distribution canals for irrigation. In most of the countries, they are 4 or 5 decades old and there is seasonal change in the amount of water that is released and the imposed restrictions. Water availability in the reservoir and release to canal show the criticality of system and crop production. Canal condition and performance of system are grouped into five categories. Size and number of *Perennial Rivers* (PeR) passing through the area and its proximity will indicate the water resource support at the time of drought. The lift irrigation from the river is one among relief measures that could be tapped during drought. The flow condition indicates the emergency resource location. Alluvium of the streambed could be used for moisture preservation. The flow level in the river is grouped into four categories.

Type of aquifer (AqT) that is present in a region gives an idea of its dependability. It is grouped into three categories of possible abundance of water and recharge efficiency. *Ground water level fluctuation* (GWF) derived from the observation wells indicates the excess pumping (drawdown) or recharge condition of the aquifer. Lower groundwater level observed during pre-monsoon indicates the total pumping/draft and resultant drawdown from the aquifer. Rise in the level after the monsoon reveals the amount of recharge that took place due to the rain. The maximum and minimum levels of the wells were grouped into five categories. Surface or groundwater *Source Dependency Level* (SDL) of revenue villages/population for agriculture/drinking water indicates the source dependency and desperate scenario that is expected in the event of shortage. If the source of supply is reservoir and the level is critical, the dependent people are likely to be worse, if the situation does not improve. Percentage of agriculture within the gross area of village and percentage of surface water or ground water or rainfed for irrigation to the gross cultivated area determines the source type to be developed in meeting the forthcoming drought events. Five categories were made in understanding the spatial stress locked regions and their proximities.

Population density (PoD) of a region decides the total resource demand and also distribution centre. It is observed that higher the density, higher the risk area of starvation death/health. Five categories have been made. *Human and livestock* (HLG) is significant in planning for the future. Their higher growth would destabilise the existing infrastructures which are planned for steady/optimal growth rate. Hence, they are grouped into five categories of growth rate. People who are affected by drought are mostly *Agriculture dependent labourers* (OcAg) and small landowners. Their concentration in a village decides the relief and subsidy distribution strategy. The percentage of people dependent on agriculture is grouped into five categories. The purchasing capacity of the population depends on their *Income* (Inco). Even though, it may vary from place to place, the gross national income used in demarcating the poverty status of the region can be considered in identifying the households that need assistance. It is grouped into five categories.

Suitable relief material storage (Stor) and distribution is another important aspect. The availability of facilities to store food, medicine and sheltering of relief workers within settlement or its proximity has been grouped into five categories. If it is nearby, the lifting of the material and distribution through volunteers will be possible when compared to far away places that needs mechanized vehicles. The availability of *trained medical fraternity* (MF)/establishment (primary health centre) and its proximity to the needy settlements would enhance the performance of relief activity. *Surface transport network facilities* (TrN) within the region and its proximity to the drought-affected settlements will improve the efficiency of the relief activities. The proximity of the said networks with individual settlements is grouped into five categories.

Table 8.2 details the various factors, classes and their weights of individual parameters that indicates and expresses the drought intensity. The weightings assigned to each parameter to reflect its importance in the occurrence of

Table 8.2: Weighting and ranking of drought parameters

Criteria	*Class*	*Class value*	*Weight*	*Criteria*	*Class*	*Clas value*	*Weight*
Period of difficulty Time series Analysis (anticipated) (PD)	>10 years	0	5	Perennial River (PeR) Flow	High	1	2
	7-10	1			Moderate	2	
	5-7	2			Low	3	
	3-5	3			Dry	4	
	1-2	4					
Frequency of Event (FE)	1-3 year	4	5	Aquifer type (AqT)	Alluvium	1	2
	4-6	3			Soft rock	2	
	8-10	2			Hard rock	3	
	10>	1					
Annual Rainfall Fluctuation (ARF)	Very high	4	8	Ground water level fluctuation (Pre & post monsoon) in meters (GWL)	0-1	1	4
	High	3			1-2	2	
	Moderate	2			2-4	3	
	Low	1			4-6	4	
					>6	5	
Aridity Index (ArI)	➢ 2	4	2	Population density (people/km^2) POD	>100	5	3
	1.5-2	3			50-100	4	
	1.0-1.5	2			30-50	3	
	<1	1			10-30	2	
					<10	1	
Palmer Drought Index (PDSI)	➢ + 4	0	8	Human and Livestock growth (% per year) (HLG)	>20	5	3
	0 to +3	1			10-20	4	
	-0.49 to 0	2			5-10	3	
	-1.0 to -2	3			1-5	2	
	-2 to -4	4			<1	1	
Evaporation (monthly in mm) (Eva)	>300	5	2	Occupation – agriculture dependent or un-organized sector (%) (OcAg)	>75	5	3
	200-300	4			50-75	4	
	150-200	3			30-50	3	
	75-150	2			10-30	2	
	<75	1			<10	1	

Land Vegetation cover	Very high	0	9	Income – (compared	➢ 75%	1	3
(NDVI)	High	1		Gross National Income)	50-40%	2	
	Moderate	2		(Inco)	25-40%	3	
	Low	3			15-25%	4	
	Very low	4			<15%	5	
Total Crop area	>70%	5	12	Food storage	<2 km	1	5
(TCr)	50-70%	4		(existing facility)	2-10 km	2	
	30-50%	3		(Stor)	10-20 km	3	
	10-30%	2			20-50 km	4	
	<10%	1			>50 km	5	
Cash crop	>0.7	5	12	Medical facility	<2 km	1	5
(Ratio cash crop/	0.7 to 0.4	4		(MF)	2-10 km	2	
cultivated)	0.2 to 0.1	3			10-20 km	3	
(CaCr)	0.1 to 0.2	2			20-50 km	4	
	<0.1	1			>50 km	5	
Crop Moisture Index	<1	5	10	Transportation network	<1 km	1	5
(CMI)	1-2	4		(distance from village)	1-3 km	2	
	2-5	3		(TrN)	3-10 km	3	
	5-7	2			10-30 km	4	
	>7	1			>50 km	5	
Surface water storage	➢ 20%	1	10				
(% of area)	15-20%	2					
(SWS)	10-15%	3					
	5-10%	4					
	<5%	5					

Steps for calculation for a grid / polygon:

1. Identify concerned parameter shown here and group into class value
2. Multiply the class value into weights and derive parameter influence
3. Add all the parameter influence

drought are given (column 4) together with rating for individual classes (column 3) which denotes the degree of hazard intensity. They represent (4 being the highest hazard and 0 the lowest). A class value (column 6) is then obtained by multiplying the figure denoting the importance of the main parameter and that for the degree of hazard represented by the particular class. The vulnerability of a region depends on the cumulative effect of individual parameters/classes. It is estimated as follows:

Drought Vulnerability (DV) = Assessment + Mitigation

$$\begin{aligned} DV = \textstyle\sum_{I=1} [&PD + FE + ARF + ArI + PDSI + Eva + NDVI + TCr + CaCr \\ &+ CMI + SWS + PeR + AqT + GWLF + PoD + HLG + OcAg] \\ &+ [Inco + Stor + MeF + TrN] \end{aligned}$$

The drought vulnerability was estimated by: (1) collection of information on various parameters and distinguishing different classes based on historical events, (2) overlaying different map layers and deriving a polygon representing surface-cover and (3) assigning class ratings for the polygon and estimating the cumulative class value. The cumulative DV was truncated into vulnerability categories such as very high, high, moderate and low depending on the complexity and requirement. Further, the influencing parameter of domination from a settlement/region can also be suitably mitigated. This procedure can be used in the vulnerability assessment for drought as well as for relief operations individually or in total. The percentage of anticipated water deficit for the village has been grouped into four categories. Weight and ranking of individual parameters in initiating the drought situation can also be used in estimating the suceptability of villages.

8.4 Vulnerability of Water Supply System

It utilizes both surface and groundwater sources and is most vulnerable to contamination and requires most of the treatment at the source. If a system utilizes a surface water source, even for only 30% of its total water supply, the system would still be classified as a Surface Water (SW) system. Surface sources (river, reservoir, pond, lake) are the most vulnerable to contamination, followed by groundwater systems under direct influence of surface water (GWUDI) and groundwater (GW) systems are considered the least vulnerable. Small water systems tend to have limited resources with which to respond to drought impacts. These systems include those in the classifications of people served - Very small (25-500), Small (501-3300), and Medium (3301-10,000).

Classification of Surface Water Supply Systems – Surface water systems were further classified according to their source water type, which are vulnerable to drought. A small system withdrawing water from lake will not be as drought susceptible as a small system whose only source is an aging reservoir with decreasing capacity. The categories used for this classification were as follows: (1) major river, (2) direct withdrawal from a river/stream, (3) river/stream with a low channel dam, (4) off-channel reservoir, (5) impounding reservoir, (6) quarry or borrow pit, (7) Lake or Lake connecting channel, (8) natural/glacial lake, and (9) a combination of sources. A system was placed in the last category only if the system's multiple sources were operated in such a way that no single source was the primary or predominant water source.

8.5 Risk

Risk management strategies concentrate on avoiding possible dangers, prevent/minimize the frequency of impacts, control/reduce the consequences of the event by way of adaptation measures, transfer the risk by way of insurance, respond appropriately to events by disaster management methods and recover or rehabilitate them appropriately. Risk analysis highlights: (1) What could happen, where, to whom? in terms of food economy analysis; household food production; household income opportunities; wealth; coping mechanisms; vulnerability analysis. (2) Who is chronically food insecure? (3) Who is vulnerable to food insecurity in the future? (4) Where, why, how many? Early warning; (5) What can effect household food security? (6) How can we know when it is coming? Emergency assessment and targeting; (7) Who is vulnerable as a result of a specific shock? Where, how many are they? (8) How do we best reach them (programme design and targeting)? Contingency planning; What can we do to prevent food insecurity (prevention)? What can we do to prepare for the inevitable (disaster preparedness); What can we do to mitigate the impact of a disaster (disaster mitigation) monitoring and evaluation? Are we doing what we planned to do? (Monitoring) Was our plan the right plan? Did we have an impact? (Evaluation). *Acceptable Risk* – A level of vulnerability that is considered to be "acceptable" balancing factors such as cost, equity, public input, and the probability of drought. *Risk Analysis* – The process of identifying and understanding the relevant component associated with drought risk as well as the evolution of alternative strategies to manage that risk. *Risk Management* – The opposite of crisis management, where a proactive approach is taken well in advance of drought so that mitigation can reduce drought impacts, and so relief and recovery decisions are met in a timely, coordinated, and effective manner during a drought.

National or regional level risk assessments have four components or composite indicators which reflect the principal elements that represent vulnerability. This is achieved in the following way: (1) The *Disaster Deficit*

Index, DDI, measures risk from a macro-economic and financial perspective when faced with possible catastrophic events. This requires an estimation of critical impacts during a given exposure time and of the capacity of the country to face up to this situation financially. (2) The *Local Disaster Index*, LDI, identifies the social and environmental risk that derives from more recurrent lower level events which are often chronic at the local and sub-national levels. This index attempts to represent the spatial variability and dispersion of risk within a country as a result of small and recurrent events. (3) The *Prevalent Vulnerability Index*, PVI, is made up of a series of indicators that characterize prevailing vulnerability conditions reflected in exposure in prone areas, socio-economic fragility and lack of social resilience in general. (4) The *Risk Management Index*, RMI, brings together a group of indicators related to the risk management performance that reflect the organizational development capacity. The objective of this index is the measurement of the *performance* of risk management. This implies establishing a scale of achievement: (a) Risk identification, *RI* (that comprises the individual perception, social representation and objective assessment); (b) Risk reduction, *RR* (that involves the prevention and mitigation); (c) Disaster management, *DM* (that comprises response and recovery); and (d) Governance and Financial protection, *FP* (that is related to institutionalization and risk transfer). *Indicators of Risk Identification:* IR1 – Systematic disaster and loss inventory; IR2 – Hazard monitoring and forecasting; IR3 – Hazard evaluation and mapping; IR4 – Vulnerability and risk assessment; IR5 – Public information and community participation and IR6 – Training and education on risk management.

Indicators of Risk Reduction: RR1 – Risk consideration in land use and urban planning; RR2 – Hydrographic basin intervention and environmental protection; RR3 – Implementation of hazard-event control and protection techniques; RR4 – Housing improvement and human settlement relocation from prone-areas; RR5 – Updating and enforcement of safety standards and construction codes; and RR6 – Reinforcement and retrofitting of public and private assets. *Indicators of Disaster Management:* DM1 – Organization and coordination of emergency operations; DM2 – Emergency response planning and implementation of warning systems; DM3 – Endowment of equipments, tools and infrastructure; DM4 – Simulation, updating and test of inter-institutional response; DM5 – Community preparedness and training; and DM6 – Rehabilitation and reconstruction planning.

Physical risk RF – Damaged area; Number of deceased; Number of injured; Ruptures in water mains; Rupture in gas network; Fallen lengths on HT power lines; Telephone exchanges affected; Electricity substations affected; *Impact factor* – Slums-squatter neighbourhoods, Mortality rate, Delinquency rate, Social disparity index, Population density, Hospital beds, Health human resources, Public space/shelter facilities, Rescue and firemen manpower, Development level; Preparedness/emergency planning. The variables and indicators for sub-national level would be similar to those at the national level, but require modifications in accordance with the spatial scale of the sub-national and urban units.

It is managed on three different levels: (1) operational level which is associated with the operation of existing systems; (2) project planning level, which is used when a new project or a revision of an existing project is planned and (3) project design level, which is embedded into the second level and describes the process of reaching an optimal solution for the project. *Contextual aspects:* Analysis of current and predicted demographics, recent hazard events, economic conditions, political structures and issues, geophysical location, environmental conditions, access/distribution of information and traditional knowledge, community involvement, organizations and management capacity, linkages with other regional/national bodies, critical infrastructures and systems. *Highly vulnerable social groups* are infants, children, aged, economically disadvantaged, intellectually, psychologically and physically disabled, single-parent families, new immigrants and visitors, socially/physically isolated, seriously ill, and poorly sheltered. *Identifying basic social needs/values* are for sustaining life, physical and mental well-being, safety and security, home/shelter, food and water, sanitary facilities, social links, information, sustaining livelihoods, and maintaining social values/ethics. *Increasing capacities/reducing vulnerability* – positive economic and social trends, access to productive livelihoods, sound family and social structures, good governance, established regional/national networks, participatory community structures and management, suitable physical and service infrastructures, local plans and arrangements, financial and material resources reservation, shared community values/goals, environmental resilience. *Practical assessment methods* – constructive frameworks and data sources including local experts, focus groups, census data, surveys and questionnaires, outreach programmes, historical records, maps, and environmental profiles.

The following scenarios are simulated over the next 20 years under the probabilistic drought risk model:

Scenario I: Maximum temperature increases by 2°C; Minimum temperature increases by 4°C; Annual rainy days decrease by 5%; Atmospheric CO_2 at 550 ppm (parts per million)

Scenario II: Maximum temperature increases by 2°C; Minimum temperature increases by 4°C; Annual rainy days decrease by 5%; Cumulative June-September (monsoon) rainfall decrease by 10%; Atmospheric CO_2 at 550 ppm (parts per million)

World Meteorological Organization (WMO, 2004) has identified the areas of challenge in risk management as: (1) related to scientific observations and improved methodologies in improving the quantity and accuracy of data in hazard mapping and impact assessment; (2) quantifying uncertainties related to forecasting hydro-meteorological extremes; (3) building up and disseminating knowledge of the effects of climate variability and change; (4) developing robust vulnerability assessment methods and (5) incorporating integrated environmental strategies in risk management.

The greatest concerns in evaluating adequacy of supply for direct withdrawals are: (1) when there is flow frequency and withdrawal information (desired nature) are not available and (2) non-availability of upstream users or other human modification that would diminish the low flow over time. When the primary source of water supply is a reservoir, there is need for a combined analysis of the storage capacity of the reservoir and the amount and duration of flow coming into the reservoir during the drought periods.

Water supply systems that depend on reservoirs are generally more likely to be susceptible to shortages during drought, primarily because of the uncertainties in: (1) calculating the capacity of the reservoir in cases where there has not been a recent bathymetric or sedimentation survey, and (2) estimating the drought inflow to the reservoir, since reservoir systems are more likely to be located in smaller watersheds which typically do not have long-term stream gauging records. In contrast, direct withdrawals without storage are more likely to be on larger streams and rivers that have long-term stream gauging records.

Deeper wells that may have been completed in drought-sensitive aquifers and wells at greater distances from other wells still could be affected by mutual interference. Water demand often increases during drought and system capability to meet increased demand and is a critical component of drought preparedness.

The best way to assess community groundwater supply's sensitivity to drought is through the use of groundwater flow models where the effects of reduced or no recharge can be examined. However, modelling requires thousands of wells as groundwater flow models are highly data-intensive. Groundwater models whether available or needing development are most necessary for those community wells determined to be most potentially drought-sensitive. *Depth:* Shallow wells are most likely affected by a lack of recharge resulting in lowered groundwater levels. Shallow wells also tend to have less available drawdown within which they can operate. Lower non-pumping water levels due to drought will further reduce available drawdown. Communities with wells less than 100 feet deep were deemed potentially sensitive, with wells less than 50 feet deep being most sensitive.

Proximity to Surface Waters: Shallow community (serving less than 10,000) wells were further identified on the basis of proximity to streams using a buffer of 1000 feet to highlight wells that receive potential recharge through streambed infiltration. These wells potentially could be affected by low stream flow during a drought or, conversely, could severely impact low stream flows during drought. Shallow wells less than 50 feet and between 50 and 100 feet deep in proximity to identified streams are highlighted. *Well Density:* Community (serving less than 10,000) wells were examined on the basis of well density, that is, the number of wells within a defined area. Typically, communities that use areally-limited aquifers will have several low-capacity wells in a very confined area. During drought, water demand typically increases, causing wells to operate for longer periods and at higher rates, increasing the effects of mutual interference. For this analysis, shallow community wells (≤100 feet deep) within 1000 feet of one another were identified (420 wells), including those wells that are also within 1000 feet of an identified stream (184 wells of which 59 are less than 50 feet deep). These community wells are deemed potentially vulnerable to drought conditions on the basis of their shallow depth, proximity to other shallow community wells, and proximity to identified streams. Sand and gravel aquifers show that most of the potentially drought-sensitive community wells are located along minor river valleys.

8.6 Drought Scenario

Scenarios are used in creative visioning of potential futures for planning and strategy. It is defined as a coherent and systematic description of a possible future expressed as narrative water resources conditions that differ from the present. It is used to picture in an exploratory way with the aim of identifying factors that will need to be taken into account in planning. Gallopin and Rijsberman (2000) developed global water scenarios based on economy, demography, technology, social life, environment and governance. Critical uncertainties that need to be scaled up are: water productivity trends, expansion of irrigated agriculture, massive increase in food production, rain-fed agriculture, dematerialisation of the economies, national/global food security, availability of cheap water-purifying technologies, public opposition to large dams, fundamental scientific discoveries and changes in human and lifestyles.

The drought scenario is derived from number of standardized variables. Vulnerability analyses indicate the susceptibility of an area to water stress due to its demand/supply and utilization pattern e.g. alpha, beta, gamma and sigma region. *Preparedness activities* are initiated based on the multi-parametric assessment on the water stress situation and the *Information on stress* – intensity and anticipated sufferings, quantum of deficit, resource availability and mobility pattern.

An exercise to construct vulnerability scenarios would address a common set of characteristics: What are exogenous drivers of vulnerability? How are the drivers mediated or distributed among vulnerable groups? How might the multiple attributes of vulnerable groups and their exposure to risks be integrated into vulnerability profiles? How sensitive are local actors and water users to different outcomes? How might changes in probability distributions of common risks (e.g., climate, water quality) be disaggregated to the exposure of specific vulnerable groups? What actions by vulnerable people might exacerbate or mediate their vulnerability? Finally, the pathways that extend present vulnerability into the future are likely to be transitions of some complexity.

Understanding the underlying causes of vulnerability is an essential in reducing the risk for a geographical location and specific group of people/ economic sector. It is relevant to the decision-making process, as it goes beyond using the indicators or techniques for the management purpose. In order to satisfy the needs of the stakeholders, different indicators, indices or a combination of the two are used in the assessment – spatial and temporal scale, nature of analysis and context decision-making process etc. Transparent and understandable methods of indicators would help experts in verifications and stakeholders to validate information in the field. As vulnerability is a dynamic process, knowledge on the current situation as well as evolution trends of the problems faced by the vulnerable people and resources at disposal or choice is essential.

Step 1 – Indicator identification and selection and compilation of required data from the desired geographical or numerical data (combination of the two) area would ensure confinement to the developed methodological framework. *Step 2* – Standardization process will transform the indicator into one scale to ensure that all indicator values are in the same direction (high values corresponds to high levels of vulnerability). Transform all the data into relative values on one scale (either % or 0 to 10) and define certain values as threshold that will represent limits or significant values with regard to different objectives. This would aid in the weighing and ranking of parameters in vulnerability profiling and also scenario/visualization analysis. *Step 3* – Choose the model, aggregation and weighing methods to develop vulnerability indicators based on the framework of analysis and objectives of the assessment – rapid assessment of groups and regions. Determine which indicators are robust in their ability to predict the likely impacts using statistical analysis. *Step 4* – Linking vulnerability assessments to adaptation strategies. Vulnerability indicators are nothing but tools to link and support decision-making and the selection and exploration of adaptation measures, options and strategies. Multi-criteria analysis can assist in the selection of adaptation options that will reduce the vulnerability of target groups based on priorities. *Step 5* – Monitoring vulnerability and adaptation strategies. The indicators selected for this purpose need to be sensitive to the anticipated changes whatever they may be. The drought scenario classification based on the select parameters could be used as thumb rule.

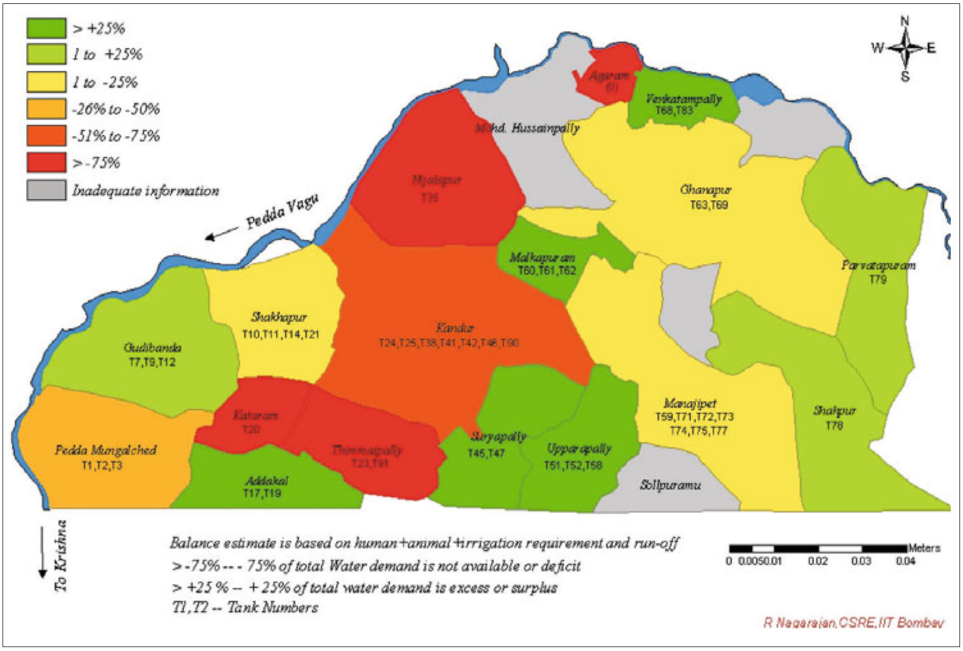


Fig. 8.4: Status of surface water in meeting the village requirments at annual rainfall of 500.

Water resource based scenario development is one of the methods for rainfed areas. It is assumed that the recorded annual rainfall is stored on the surface storage systems or underground storage system and used for consumption. Further it is assumed that if the entire rainfall is uniform across the space, storage system exists for collection and conservation. Water demand from the crops, human and livestock is calculated using standard tables. Figure 8.4 shows the water availability deficit (in percentage) with reference to demand of the individual villages. The deficit is estimated with reference to annual rainfall, as percentage of availability or supply with reference to demand. If it is more than the demand, it is grouped as green and shades of red for deficit. Supplementary supplies (groundwater source or water transport or transfer) are not considered. This could aid in strengthening the clusters of village by way of resource-sharing method.

8.7 Decision-making

It goes with the associated responsibility and resources at the disposal of the person – *people associated* with decision making. The level and accuracy of

Fig. 8.5: Scale of information requirements for micro and macro level decision-making process.

details vary from one farm plot to village boundary etc. Scale of information and requirements are summarized in Fig. 8.5. The decision-makers required identifying the relevant information, models and methods, extract meaningful information from image sets, retrieve spatial data and create and update knowledge for high level decisions. The nature of climate variability is inherently uncertain. The uncertainty of climate forecast makes it difficult to make a decision, even when the forecast suggests higher chances of having one category of rainfall.

Decision-maker always needs to consider all aspects of the forecasts. A decision that is based only on the most likely outcome of the forecast could have many undesirable consequences. Every year, prior to the beginning of the rainy season, the water levels are adjusted in the dam in anticipation of incoming stream flow fed by rainfall over the coming months. In the absence of a climate forecast, a release of 50% is usual. If you leave too much water in the reservoir, there is a risk of having to release water very quickly. If it is released too much in advance of the season, recoup of water to fill the dam back up is not possible.

Decision I – Release 10% of the allowable water behind the dam

Observed rainfall	*Potential societal outcome*
Above normal	Down-stream farmers get reduced irrigation in the important dry season and are angry. They are able to plant after rains begin.
Near normal	Down-stream farmers go with reduced irrigation in the important pre-season period and are angry. Harvests of the second crop during the rainy season are normal.
Below normal	Down-stream farmers go with reduced irrigation in the important pre-season period and are angry. Very little is harvested during rainy season either.

Decision II – Release 30% of the allowable water behind the dam

Observed rainfall	*Potential societal outcome*
Above normal	Down-stream farmers have almost enough irrigation during dry season and are able to irrigate some but not all of their land.
Near normal	Down-stream farmers have almost enough irrigation during dry season and are able to irrigate all of their land. Harvest during rainy is normal.
Below normal	Down-stream with reduced irrigation in the dry season and are angry missing planting opportunities. Very little is harvested during rainy season either.

Decision III – Release 70% of the allowable water behind the dam

Observed rainfall	*Potential societal outcome*
Above normal	Down-stream farmers have plenty of irrigation during dry season and are able to irrigate all of their land. Crop production during the dry season is excellent.
Near normal	Down-stream farmers have plenty of irrigation in the dry season and are able to irrigate all their land. Crop production during the dry season is excellent.
Below normal	Down-stream farmers have plenty of irrigation during dry season and are able to irrigate all their land. Production from the irrigated crops in the dry season sustains then through the drought-stricken rainy season in which rain-fed crops suffer from water stress.

A decision rule is a procedure that allows for ordering alternatives (Starr and Zeleny, 1977; Chankong and Haimes, 1983) that dictates how best to order alternatives or to decide which alternative is preferred to another. It integrates the data and information on alternatives and decision maker's preferences into their overall assessment. A multi-criteria decision problem involves ordering the set of outcomes and identifying the decision alternatives yielding these outcomes. Spatial decision-making rules can be categorized into multi-attribute and multi-objectives decision rules. The Multi-attribute Decision Rules (MADM) choose the best or the most preferred alternatives, to sort out alternatives that seem "good" and/or to rank the alternatives in descending order of preference using simple additive weighing method, value/ utility function approaches and the analytic hierarchy process, in addition to ideal point methods and concordances methods. Additive decision rules are the best known and most widely used MADM methods in GIS based decision making. Multi-objective Decision Rules (MODM) define the set of alternatives in terms of a decision model consisting of a set of objective functions and a set of constraints imposed on the decision variables. A number of MODM decision rules exist for tackling spatial multicriteria decision problems such as value/utility function methods, goal programming, interactive programming, compromise programming and data development analysis. A comprehensive review is given in Chankong and Haimes (1983). Figure 8.6 shows the step-wise water availability and stress.

Vulnerability and risk analyses indicate the geographical position and quantum of resources required during the crisis. Guidelines for the relief and assistance disbursement are based on the scientific and sociological inputs accepted by the political institutions.

8.8 Contingency Drought Plans

It is defined in order to establish objective thresholds supporting the selection of specific measures related to an indicators system and is carried out by: Determining the indicators and thresholds that will establish the starting point, the ending point, and severity levels of the exceptional circumstances, in addition to thresholds of pre-alert and alert levels; establishing measures to take during the pre-alert and alert phases in order to prevent deterioration of water status; execute measures in arresting the deterioration of water status; and restoring water body to its original status; make a summary of the effects and measures taken and subsequently revise and update the existing drought management plan. In the core of possible measures, some are emerging due to their important impact on the biggest water consumers and to their short-term effects: Drought hazard management and crisis response framework for a groundwater aquifer includes *management component* such as determination and maintenance of pumping reserves, purchase of water from adjacent supply systems and identification of cheaper water use alternatives; *preventive measures* such as on-line quality monitoring, optimum disposal means, suitable location of industries and pre-treatment of industrial wastes and corrective measures such as identification of pollution sources, information dissemination on hazard situation, alternative source of supply and mitigation of damaged aquifers.

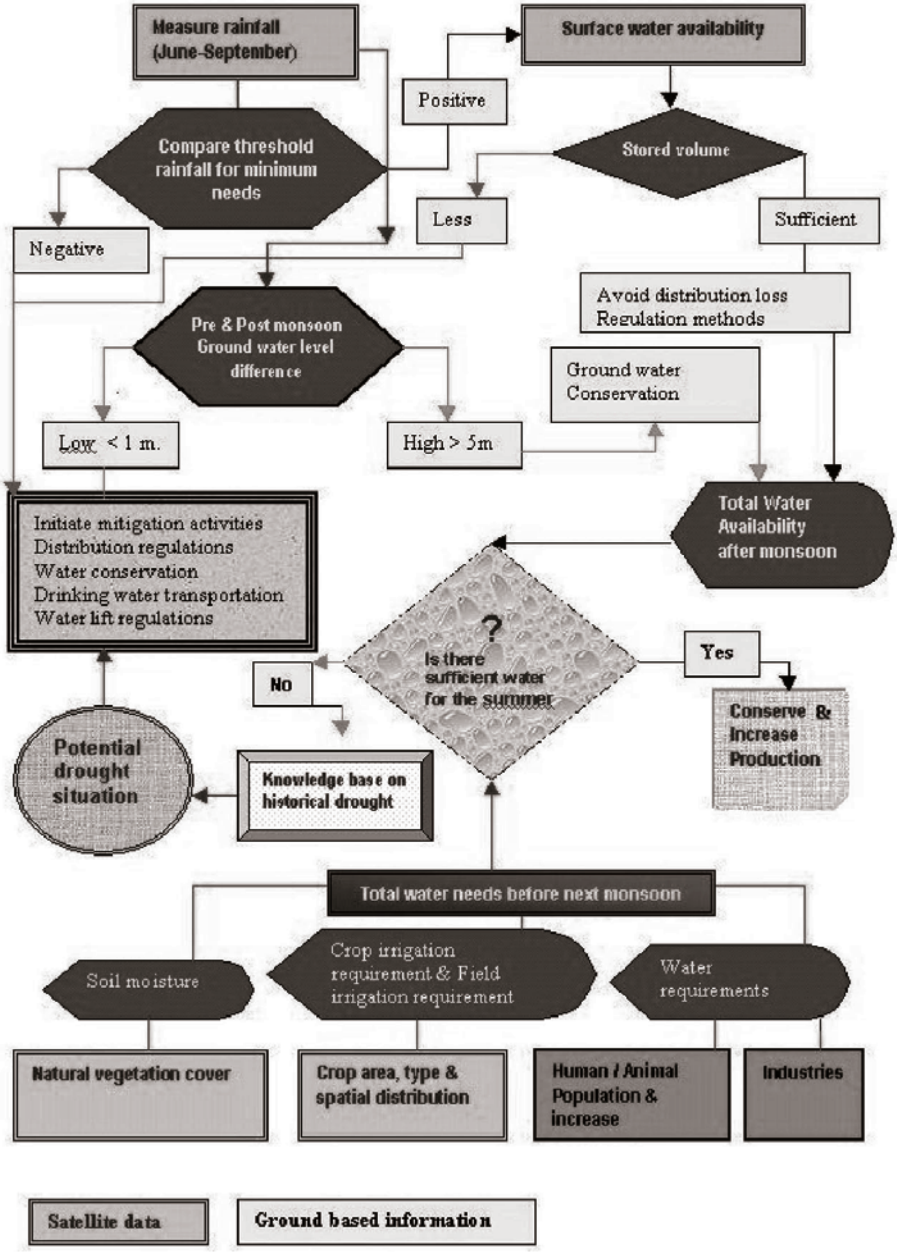


Fig. 8.6: Flow chart showing the self-assessment of water availability situation.

Demand-side measures are addressed by: Changes in water consumption promoting subsidies; Reduction of leakages in the distribution networks; Improvement of irrigation technologies by improving agricultural management, optimizing soil water utilization and irrigation, and reduce water consumption (e.g. crop rotation, genetic variety); Promotion of improved waste water reuse where appropriate; Natural storage improvement and water saving; Evaluation of the advantage of setting up water banks and quota systems; and Development of education and awareness campaigns. *Supply-side measures* are addressed by: Preservation of the functioning of natural catchments, aquifers and restoration; Improvement of an efficient use of existing water infrastructures; Water recharge aquifers; Setting up an obligation for using a costs/needs/advantages/alternative solutions analysis with economic, environmental and social impact for every project of new water resource creation; and Evaluation of effectiveness and efficiency of the proposed measures.

Characteristics of weather risk on farm: Annual average rainfall (in mm); Probability of favourable soil moisture; Length of crop growing season; Incidence of crop failure (average of 3/5 years); Agriculture plots with complete crop failure (%) and Plots with partial crop failure (%). *Indicators of spatial diversification:* Scattered land fragments per farm (number) and fragments per farm by distance from villages (no.) 0.8 km, 0.8 to 1.6 km and >1.6 km. *Crop based diversification:* Extent of intercropping (%): Gross crops planted and gross mixed crops planted. *Occupational and Institutional adjustments:* Occupation and income per household, Houses with more than one occupation and Household with seasonal migration.

Risk management involves choosing among alternatives to reduce the effects. Among the most important production and market risks is *yield risk*, which refers to the impact of uncontrollable events that are often related to the weather (drought, extreme temperatures, floods and hail) and have an impact on the potential crop yield. The combination of yield (production) and price (market) risk results in income instability and cash-flow variability. These risks can be countered by on-farm strategies (e.g. maintaining cash reserves, improved production efficiency or diversification) and risk-sharing strategies (e.g. vertical integration, production contracts, marketing contracts or future contracts). *Yield insurance* is one type of insurance in agriculture. This allows the calculation of a probability distribution of a loss occurring, based on historic data. One important requirement that must be met for a risk to be insurable is that the implications of systematic risks must be overcome. Systematic risks are dependent risks, i.e. damages that occur at a national scale have the effect that premiums paid into a pool may not be sufficient to cover the loss in the case of drought or flood. Under these circumstances, government intervention is required.

Crop Insurance

Crop insurance policy is one of the risk management options that provide policies for more than 100 crops. Non-insured Crop Disaster Assistance

Program (NAP) provides financial assistance to producers of non-insurable crops when low yields, loss of inventory, or prevented planting occurs. Multiple-peril crop insurance (MPCI) policies are also available for most insured crops. The premium is calculated based on Yield-based Insurance Coverage with the help of following parameters:

Actual Production History (APH) – Producers insure crops against yield losses due to natural causes such as drought, excessive moisture, hail, wind, frost, insects, and disease. The farmer selects the amount of average yield that he wishes to insure; from 50-75% and the predicted that is to be insured (55 and 100% of the crop price). If the harvest is less than the yield insured, the farmer is paid an indemnity based on the difference. Indemnities are calculated by multiplying this difference by the insured percentage of the established price selected when crop insurance was purchased. *Group Risk Plan (GRP)* – use a county index as the basis for determining a loss. When the county yield for the insured crop, as determined by National Agricultural Statistics Service (NASS), falls below the trigger level chosen by the farmer, an indemnity is paid. Payments are not based on the individual farmer's loss records. Yield levels are available for up to 90% of the expected county yield. However, individual crop losses may not be covered if the county yield does not suffer a similar level of loss. This insurance is most often selected by farmers whose crop losses typically follow the county pattern.

Dollar Plan provides protection against declining value due to damage that causes a yield shortfall. Amount of insurance is based on the cost of growing a crop in a specific area. A loss occurs when the annual crop value is less than the amount of insurance. The maximum dollar amount of insurance is stated on the actuarial document. The insured may select a percent of the maximum dollar amount equal to CAT (catastrophic level of coverage), or additional coverage levels. *Rainfall Index* (RI) is based on weather data that reflects how much precipitation is received relative to the long-term average for a specified area and time-frame. Pilot studies of the region are considered. *Vegetation Index* VI is based or normalized difference vegetation index (NDVI) data derived from satellites observing long-term changes in greenness of vegetation and the different weather patterns, with pilots available in select counties. *Revenue Insurance Plans* – All revenue-based options determine revenue differently. See each policy's provisions for their definition of revenue. *Adjusted Gross Revenue* (AGR) insures revenue of the entire farm rather than an individual crop by guaranteeing a percentage of average gross farm revenue, including a small amount of livestock revenue. The plan uses information from a producer's Schedule and current year expected farm revenue, to calculate policy revenue guarantee.

Crop Revenue Coverage (CRC) provides revenue protection based on price and yield expectations by paying for losses below the guarantee at the higher of an early-season price or the harvest price. *Group Risk Income Protection* (GRIP) makes indemnity payments only when the average county revenue for the insured crop falls below the revenue chosen by the farmer. *Income Protection* (IP) protects producers against reductions in gross income when either a crop's price or yield declines from early-season expectations. *Revenue Assurance* (RA) provides dollar-denominated coverage by the producer selecting a dollar amount of target revenue from a range defined by 65-75 percent of expected revenue. To determine coverage, see the policy provisions. *Catastrophic Coverage* (CAT) pays 55% of the established price of the commodity on crop losses in excess of 50%. The premium on CAT coverage is paid by the Federal Government; however, producers must pay a administrative fee for each crop insured.

The following information obligations from producer are required: report acreage accurately, meet policy deadlines, pay premiums when due and report losses immediately; Expectations – producers will receive; accurate answers to questions on types of coverage; prompt processing of their policy, and timely payments for covered losses; and Important Deadlines – Sales closing date, last day to apply for coverage; Final planting date - last day to plant unless insured for late planting; Acreage reporting date – last day to report the acreage planted (if not reported, insurance will not be in effect); and date to file. The following explanations are given: End of insurance period – latest date of insurance coverage; Payment due date – last day to pay the premium without being charged interest; Cancellation date – last day to request cancellation of policy for the next year; Production reporting date – last day to report production for Actual Production History (APH); Debt termination date – date insurance company will terminate policy for non-payment.

References

Benayoun, R., Roy, B. and Sussnab, B. (1966). ELECTRE: une methode pour guider le choix enpresence de points de vue multiples. SEMA (Metra International). *Direction Scientifique, Note de Trava*, **49**, Paris.

Chankong, V. and Haimes, Y.Y. (1983). Multiobjective decisions making theory and methodology. North-Holland, New York.

Cutter, S.L. (1996). 'Vulnerability to environmental hazards'. *Prog. Hum. Geogr.*, **20**, pp. 529-539.

Gallopin, G.C. and Rijsberman, F. (2000). Three global water scenarios. *International Journal of Water*, **1**, pp. 16-40.

IPCC (Intergovernmental Panel on Climate Change) (2001). Climate change 2001: The scientific basis. Contributed by Working Group I, Third Assessment Report., IPCC, Geneva, pp. 881.

Starr, M.K. and Zeleny, M. (1977). MCDM: State and future of the arts. *In:* M.K. Starr and M. Zeleny (Eds), Multiple criteria decision making. Amsterdam: North-Holland, pp. 5-29.

Wilhite, D.A. (2000). Drought planning and risk assessment: Status and future directions. *Annals of Arid Zone*, **39**, pp. 211-230.

Wilhite, D.A. and Vanyarkho, O. (2000). Drought: pervasive impacts of a creeping phenomenon. *In:* Drought: A Global Assessment. Natural Hazards and Disasters Series, Wilhite, D.A. (ed.), Routledge Publishers, UK.

Further Reading

Alter, S. (1980). Decision Support Systems: Current Practice and Continuing Challenges. Addison-Wesley, Reading USA.

American Water Works Association (2002). Drought Management Handbook. AWWA, Denver, CO, 126 pp.

Antony, R., Berger and William Iams (1996). Geoindicator. AA Balkema, Rotterdam.

Eastman, J.R. and Jiang, H. (1996). Fuzzy measures in multicriteria evaluation. Proceedings 2nd International Symposium on Spatial accuracy assessment in Natural resources and Environmental studies. May 21-23, Fort Collins, Colorado.

Hokkanen, J. and Salminen (1997). ELECTRE III and IV decision aids in an environmental problem. *J. Multi-criteria Decision Analysis*, **6(3)**, pp. 215-226.

Janssen, R. (1992). Multi-objective decision-support for environmental management. Dordrecht, The Netherlands, Kluwar Academic.

Saaty, T. (1980). The Analytic Hierarchy Process. McGraw Hill, New York.

Vieux, B.E. and Kalyanapuram, M.V. (1992). GIS analysis of routes for transportation of hazardous materials. Proceedings of the 8th Conference held in conjunction with A/E/C systems. American Society of Civil Engineers, New York, pp. 168-173.

Vincke, P. (1989). Multi-criteria decision – Aid. Chichester, West Sussex, England, Wiley.

Wilhelmi, O.V., Hubbard, K.G. and Wilhite, D.A. (2002). Spatial representation of agroclimatology in a study of Agricultural drought. *International Journal of Climatology*, **22**, 1399-1414.

Winrock International India (2005). A Review of Vulnerability to Climate Change and Adaptation Strategies in India. Study carried out for World Bank.

9

Resources, Drought Events and Management Profile of Countries

Arable land is limited in the arid and semi-arid areas that cover most of the regions in the world making agriculture potentially highly vulnerable to climate change. Many of the region's irrigation systems are under considerable environmental strain due to salinity, water logging or over-exploitation of ground water. Ground water, including non-renewable fossil water, is of primary importance in most countries of the region. The methods of management vary from country to country. Water use insufficiency is often due to mismanagement, corruption, lack of appropriate institutions, bureaucratic inertia and a shortage of investment in both human capacity and physical infrastructure. An over-view of the country's resources' profile, natural resource (water and agriculture), rainfall and temperature and the drought events, collated from print and web sources are summarized in this chapter.

9.1 Africa

The equator that passes through Africa divides it into two equal parts (lengthwise) and makes the climatic and physical conditions on the north and south of it as the same. The Kalahari Desert is on the south and Sahara on the north; the Karoo matches the Maghreb, while the conditions in the Cape area are almost identical to those of the Mediterranean region. Africa is the only continent that straddles the equator and therefore incorporates both the Tropic of Cancer and Capricorn. The climate south of the equator mirrors that of the north of the equator but the shape of the northern half of Africa reduces any maritime influence. The subtropical high pressure systems on both sides of the equator generate two wind systems that converge on the equator in a zone termed Inter-Tropical Converge Zone (ITCZ). From the north, Subtropical High Pressure Belt zone blows the Northeast Trade Winds (locally called Harmattan). From the south Sub-tropical High Pressure belt zone blows the Southwest Trade Winds (locally called Monsoon). The Monsoon winds are moist and bring rainfall to the coasts of West Africa. *Rainfall* distribution in the southern hemisphere averages from 5000 mm in the coastal strips of Sierra Leone, Liberia, Nigeria, Cameroon and eastern Madagascar to 500 mm in the Sahel and 200 mm or less in the arid regions (Sahara and Kalahari). Mean rainfall in Africa is about 670 mm, but there are great regional disparities. Mean annual temperature is in 3°C to 5.5°C range for a greater part of the continent with <3°C in the forest belt around the equator. Climate is determined by the wind system, topography, and pressure of large water bodies. The heaviest rainfall occurs near the equator, especially in the region from the Niger Delta to the Zaire River basin and central Zaire. The deserts are dry, and water is deficient throughout the year. The semi-arid region is most affected by droughts.

It has nine major river basins – Nile, Congo, Zambezi, Okovango, Orange, Volta, Niger, Lake Chad and Senegal – as well as small ones draining the east coast and discharging their waters into the Indian Ocean. The climatic variability has an impact on the runoff characteristics of the continent. The high rate of evaporation, about 570 mm/year, reduces the effectiveness of rainfall and introduces marked seasonality in the river regime. Nearly all are international basins, some traversing more than eight countries. Total river runoff amounts to 4.2×10^{12} m^3/year, and total stable runoff is about 2.1×10^{12} m^3/year (Endersen and Myhrstad, 1987). The main characteristic of the runoff is its seasonality, which makes harnessing water resources possible only through the use of reservoirs. Total volume of lakes is 30,567 km^3, covering a surface area of 165,581 km^2. All the lakes in Africa are international, shared by more than two countries, except Lake Tana in Ethiopia.

Ground water contributes approximately 30% of total runoff, although this proportion varies considerably within different geographical zones. In arid and semi-arid areas, surface runoff is more than 90% of the total runoff. In arid and semi-arid regions of Africa, more than 40% of the total ground water is fossilized water. The hydro-geological formations that form a part of deeper aquifers are sedimentary basins, the crystalline basement-complex rocks, and volcanic formations. The sedimentary basins occur in the arid and semi-arid areas of Africa, the Sahara and the Kalahari. The crystalline basement-complex rocks are extensive and less productive. The aquifers occur within the weathered residual overburden, usually about 15-30 m thick, and along fractures that typically extend downward some 60 m (Wright, 1985). The rates of recharge vary considerably, although typical rates are 3-10% of the mean annual precipitation (Chilton and Smith-Carington, 1984).

The richest aquifers produce 12-15% of the total annual precipitation. However, the boreholes drilled in fractures have very high yields during the wet seasons but generally dry up during long droughts. Some of the aquifers that are shared by the neighbouring countries are: The Iullemeden system shared by Mali, Niger and Nigeria; the SASS aquifer shared between Algeria, Tunisia and Algeria; different Karoo-Kalahari systems shared by Namibia, Botswana and South Africa and by Angola-Zambia respectively; the Chad Aquifer systems shared between Chad, Cameroon, Central African Republic Libya Niger, Nigeria and Algeria; the Nubian Sandstone aquifer shared by Egypt, Libya, Chad and the Sudan; the Benin-Togo Coastal Aquifer; the Djibouti-Ethiopia shared basalt aquifer; the Kenya-Tanzania basalt aquifer; and the Merti aquifer (Kenya-Somalia).

Renewable fresh water availability on an annual basis exceeds about 1700 m^3/person and will suffer only occasional or local water problems. Below this threshold, countries begin to experience periodic or regular stress. The daily level of water-supply services also varied from 15 lts/person in Angola to about 270 lts/person in Madagascar; in the rural areas, the average varied from 20 to 40 lts/person. There are abundant water resources available within the humid tropics. Drought and famine affected areas in Africa are illustrated in Fig. 9.1.

About 2.817×10^9 ha of the arable land is under cultivation and 68% of population is currently engaged in agriculture. Irrigation takes up 88% of the total water withdrawals. With the greatest part of African agriculture under rainfed crop farming, food insecurity is largely caused by variability of rainfall. 53% of all irrigated land is under cereals, the importance of irrigation to obtain food security must not be underestimated. The current emphasis on irrigation in Botswana, Burkina Faso, Ghana, Kenya, and Somalia is aimed at rehabilitation and expansion of old schemes. In Egypt, some efforts are

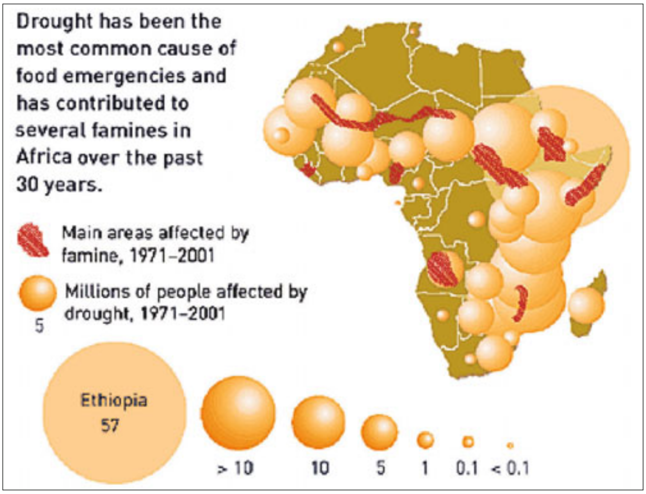


Fig. 9.1: Drought and famine in Africa during 1971-2001.
Source: UNEP/GRID-Arendat

being directed towards improving irrigation efficiency. The construction of Nanatali Dam on Senegal River will increase Senegal's irrigable land by 400,000 ha, and Mali's by 300,000 ha. Egypt and Sudan will irrigate a further 2.0×10^6 ha in the Nile Valley, and 400,000 ha will be irrigated in Uganda, Tanzania, and Kenya.

In the dry areas of Africa, irrigation consumes 100 m^3 of water per tonne of biomass produced and this activity will deplete the amount of water available for other uses. In South Africa, the lower portions of major rivers, such as Modder, Rietz, Vaal at Douglas, and Orange, are at various stages of salinization as a result of irrigation and urban development. No irrigation scheme in arid and semi-arid areas can be successful for long periods unless it has adequate drainage. Water problems are caused by contamination and over-exploitation. Contamination of ground water is difficult to detect, and monitoring is costly, time consuming, and not always effective. Contaminants coming from agricultural, urban, and industrial land uses is the reason for decline in freshwater quality. Over-exploitation of freshwater resources occurs in areas where there is scarcity. People are increasingly moving into areas of marginal productivity.

Major droughts occurred in the 19th century; the most dramatic one, in the 1980s, affected 20 countries and some 30 million people in sub-Saharan Africa. In Gambia, drought reduced recharge of the ground water, necessitating further deepening of wells. These wells then collapsed, aggravating the competition for water. Subsequent overuse of wells caused salt-water intrusion in those boreholes that survived the drought period. The responses to water stress are: (1) *Reallocation of water from irrigation* to industry as irrigation consumes more than 80% of all the water by setting the tariffs paid by agricultural users high enough to force them to conserve. (2) *Population policy* that takes into account available freshwater resources and the rate at which such resources may be developed and defined priorities to target specific populations for increased water activity. (3) Methods to *improve efficiency* and reduce water losses – Today, only 25% of the water is lost, and 85% of bills are paid. Water systems tend to operate more efficiently if the responsibility for daily operations and that for capital investments are kept separate. (4) *Water-resource planning* with adequate information for understanding both the hydrologic systems on which water-resource management is built and the nature of the interactions between the natural and the socioeconomic systems. (5) *Involvement of consumers* - Consumers who know the status of the natural resource and are informed about the limitations of their actions will make rational decisions. (6) *Water-management issues* – Water policy – A national water policy giving a clear direction provides the necessary linkages between the water sector and critical areas of the economy, including health, agriculture, sanitation, and rural development.

Botswana and Morocco have the necessary instruments that define water use, institutional responsibilities and coordination; issuance of permits for water abstraction and use; treatment of effluent and its safe discharge; groundwater exploration; water abstraction and use; tariffs; population and water use; water and health; the role of women and popular participation; wetland and aquatic ecosystems; international water courses and regional cooperation; and training and registration of water scientists. (7) *Legislation* – African countries have laws that require permits or licences for abstracting water from either surface or groundwater sources and for discharging waste or effluent into a water body. These laws are inadequate as the: Legislation governing rational use and management and responsibilities for implementation and monitoring of water resources is scattered in various enactments/departments. Complementing institutions are poorly organized and have no resources for monitoring, policing, and punishment of offenders. Rules and regulations have not been elaborated to provide a firm basis for applying the laws. Appropriate quality standards have not been set for effluent discharges. Penalties for offenders are lenient and constitute an inadequate deterrent. Botswana is one country that revised its entire water law in 1990.

(8) *Development of human resources* – Human resource development policies need to be strengthened to ensure more effective use of trained personnel and improved employment conditions. (9) *Demand management* encompasses mechanisms by which water is allocated efficiently to different user groups. (10) *Price mechanisms* – Although water has traditionally been considered a common good, shortages have occurred and the cost of getting water from alternative sources has increased, so its value has gone up. Loans for irrigation were mainly made to the countries north of the Sahara with proven irrigation cultures, whereas loan disbursements for water supply were mainly for urban water, thereby explaining the disparity in service between urban and rural areas. Absence of cost-recovery measures meant that 82% of the countries' urban water systems relied on the central government to subsidize their operation and maintenance costs. For the rural areas, all countries charged some tariff, but 46% charged tariffs that covered only part of the operation and maintenance costs.

Pollution-permit trading is a way of reducing pollution and improves the quality of decision-making in integrated water-resource management. Under this system, the government issues a fixed number of pollution permits, which are then bought and sold at market prices by firms. *Use of marginal water and reuse of wastewater* – In Algeria and Tunisia, drainage water from irrigated fields is already being recovered and reused in irrigation systems, and in Egypt, Libya, Tunisia, and Morocco. Greater Cairo generated 0.9×10^9 m^3 of wastewater in 1990, for example; this is expected to increase to 1.93 10^9 m^3 by 2010. Similarly, Morocco and Tunisia discharged 555×10^6 and 227×10^6 m^3 of wastewater, respectively, in 2000, and all the urban centres in Botswana combined will produce 66.4×10^6 m^3 of wastewater by 2020. In Tunisia, about 3000 ha has been irrigated, under controlled conditions, with secondary-treatment wastewater effluent; this uses about 7×10^6 m^3 of treated effluent per year. Wastewater is also used to irrigate the greenbelt around Khartoum, Sudan, and 1000 ha of Egyptian farmland. Morocco and Tunisia, for example, charge farmers fees for using reclaimed wastewater (Khouri, 1989).

Desalinization of sea water – A capital- and energy-intensive source of fresh water, is growing in importance in oil-rich countries such as Egypt, Libya, Tunisia, and Morocco having desalinization plants. Desalinization is still three to four times more expensive than conventional methods of obtaining fresh water. Both ground water polluted by nitrates and pesticides and municipal water are treated to make ultra-pure water for the electronics industry. *Regional cooperation* – Effective water management requires a broad plan for an entire river basin. Most river basins in Africa are shared by two or more countries. Cooperation in water resource management needs to be pursued at two levels: through comprehensive management of domestic supply and demand; and regional planning and arrangements to import water from surplus countries to deficit countries. Competition and conflicts in water use generally emerge when there is a lack of cooperation, leading to international tension.

There are 54 trans-boundary river-lake basins in Africa. Among these basins, only a handful – Senegal, Gambia, Niger, Chad, and Kagera – are overseen by intergovernmental organization, with the exclusive task of planning for integrated development of natural resources, energy, and other water-related infrastructures. Among the nine countries in the Nile basin, there are no agreements, nor is there any forum for negotiations on how its water should be shared. The risks of new tensions and conflicts, especially in North Africa, are clear, and the need for cooperation and agreement on the use of water resources has never been greater. Capacity-building and institutional arrangements are needed in these organizations to strengthen the planning units and improve policy and legal frameworks. The first of these barriers is the difficulty of devolving sufficient responsibilities for water management to local authorities and community institutions. In Kenya, the Lake Naivasha Riparian Owners' Association has been deliberating on land and water disputes since 1939. Presently, the association is involved in a three-phase study that will culminate in the formulation of an environmental management plan.

Capacity-building and technical assistance are recommended to improve human resource development: Education and training programmes on pollution control and hazardous-waste disposal need to be established, and existing ones need to be strengthened. Community-based management institutions, such as water users' associations, should be given support to manage freshwater resources. The responsibility for planning and managing water resources should, therefore, be decentralized and left to the communities and their institutions. Safeguards on freshwater management must be introduced at the local level. Demand management through water pricing, cost recovery, privatization, and community management, should be introduced. Water use efficiency and conservation strategies are: (1) Strategies for improved efficiency and water conservation must be instituted. (2) Standards for water recycling and the use of water of marginal quality need to be established. (3) Modalities for reallocation of water rights must be developed. (4) External and internal sources of funding need to be mobilized and appropriate use of water-generated public funds need to be ensured, with emphasis on transparency and accountability.

9.2 Tropical Countries

Afghanistan

It is popularly called the land of mountains or the Switzerland of Asia. The climate is cold in winter, hot and dry in the summer. Annual rainfall of 381 mm is normally scanty and much of the precipitation is as winter snow and spring rains. Southern part of Afghanistan is receiving the least rainfall (100-300 mm per year) followed by western (200-400 mm) and northern parts. Strong winds from April to August have a severe desiccative effect. Many historical rainfall data are difficult to get and some of them were lost. Amu Darija, Hamrud, Kabul, Helmand and Farrahud rivers drain the surface run-off from the rugged areas. Irrigated areas are at the base of the mountains and canal irrigated fields along the banks of Helmand river as far south as the town of Garmseer. Most of the rivers and watercourses are nearly in dry condition. Underground water tables have decreased significantly, impacting agricultural producers who rely on springs and karezes. Safe potable water is a serious concern, as many wells have dried up completely. There was a marked reduction in the number of shallow wells, deep wells, karezes and hand pumps during the drought. In the Zaranj district of Nimroz province, people buy water from suppliers for 2 to 3 Afghans per litre. The decrease in water sources has affected the farm lands (in high and lowland) in the downstream canal areas and karez irrigated areas leading to death of fruit trees and vineyards. Yield reductions upto 75-100% of the normal harvest have been recorded in these areas.

Shallow soils and barren rocks found in these regions do not retain moisture. Lack of vegetative cover and the high population density in the region make this area highly vulnerable to droughts. The agricultural land is 12% of Afghanistan's land area and 5% of the total agricultural land is under irrigation (both intensive and intermittent) and 7% under rain-fed agriculture

(Bhattacharya et al., 2004). Lack of snowfall during the winter and less-than-normal rain has led to decreased water availability for irrigation in the south during summer. Most of the agriculture is carried out through canal systems along the river courses. 60%, 40%, 20% and 15% of cultivation (major crops – wheat and barley) activities in Uruzgan, Zabul, Kandahar and Helmand provinces rely on (natural springs) karezes and intermittent flood irrigation (WFP, 2003). Secondary crops include maize, cotton, beans, pulses, melons, cumin and poppy. Vineyards, pomegranate and almond orchards are also found in the area.

Drought – Four of the five years during 1999–2004 except 2003 were drought years in Afghanistan. Southern and central parts of the country are drought prone area (Fig. 9.2). The worst affected areas are in the provinces of Kandahar, Zabul and Helmand. Large number of people have lost their rainfed wheat crop and their livestock mainly in Kandahar and Zabul provinces due to lack of water and feed. The rural population suffered from shortage of potable water and falling groundwater levels and many of the shallow open dug wells (up to 30 metres deep) dried up. Owing to drought conditions and agriculture-related hardship, poppy cultivation is on the rise as a mechanism to maximize the profits from shrinking cultivable area. Crop diversity was reduced by 71% and productivity by over 50% in the western provinces of the country. Because of the lack of employment opportunities,

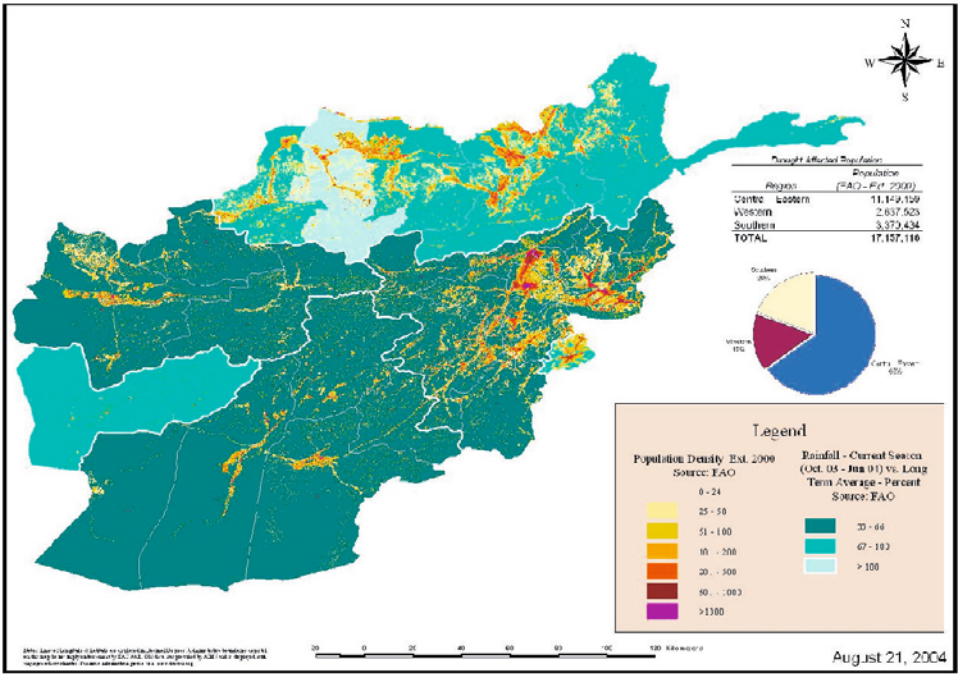


Fig. 9.2: Drought affected areas of Afghanistan.
Courtesy: UNOSAT

migration was rampant and desperate measures, such as indentured child labour and early marriage of girls, have increased.

Mitigation – The traditional coping mechanisms for people in the south are close to exhaustion. They have sold belongings – agricultural lands, livestock, and household assets – taken loans and mortgaged their lands. In many areas, people are facing shortages of safe potable water due to the decrease of ground water. Drinking water is salty and unpalatable in the Sange Atash district of Badghis province. In many shallow wells, the water levels have dropped up to 12 metres and salty water has percolated into the wells. Many shallow wells up to 30 metres in depth are dry. In some parts of Khost, people have to travel up to 12 km to collect drinking water from the closest usable source. In urban areas, the old water supply systems were not able to cope with the expanded city limits. Irrigation potential of the existing water bodies and storage dams has been greatly reduced. Dahla dam at Kandahar province is heavily silted and the capacity of the reservoir has decreased. Operational and semi-operational karezes need cleaning and improvement. In some provinces, like Helmand, Kandahar, Zabul, Urozgan and Ghor, an increasing number of landlords are engaged in poppy cultivation. In southern and western parts of the country, the most active agricultural months are March through October, when there is hardly any precipitation. Nearly all precipitation comes from November through early March and comes only in 50-60 hours a year.

This water needs to be captured and stored until the growing season. The traditional snow-water harvesting systems *cha* (winter snow) in underground storage tanks (upto 20 metres) are not functional in Ghor and Badghis. Local shuras (*shuras* is a religious and administrative entity, whereby members of the community select their leader(s) to represent them) and water waqils (*waqil* – water judge) are selected by the villagers usually for a year for dealing with water related issues. The waqil's main function is to ensure equitable distribution of water from the canal to the fields as per defined rules observed by the local community. They were functioning well in the past, but were not very effective in handling water issues, especially in the recent drought years. At the same time, people still feel that shuras can play a significant role in community-based drought management. *Waqils* are also suffering due to low production. Their income, often paid in kind by farmers, has reduced significantly. Consequently, they have lost interest in that work.

Australia

Australia has landmass of 7,617,930 km^2 and 34,218 km coastline is on the Indo-Australian Plate and surrounded by the Indian and Pacific oceans. The largest part of Australia is desert or semi-arid lands commonly known as the outback. It is the flattest continent, with the oldest and least fertile soils, and is the driest inhabited continent. Only the southeast and southwest corners of the continent have a temperate climate. Most of the population lives along the temperate southeastern coastline. The landscapes of the northern part of the country, with a tropical climate, consist of rainforest, woodland, grassland, mangrove swamps, and desert. It has a number of distinct climatic zones such as the summer dominant tropics and sub-tropics to the north; the Mediterranean climates to the south; the arid and semi-arid regions in the middle of the continent; and areas of high rainfall on coastal fringes and in the ranges of the east of Australia. The appearance of an El-Nino is very often associated with below average rainfall over much of eastern Australia and also linked to a swing in the mean atmospheric pressure difference across the Pacific Ocean called the Southern Oscillation (Allen, 1996). Perth in Western Australia could become the world's first ghost metropolis, an abandoned city with no more water to sustain its population. The rainfall zones are classified into Southern arid, Central arid, Southern Mesic, Northern semi-humid, east-coast semi-humid, Northern sub-coastal humid, Northern coastal humid, Top end and Cape York humid, wet tropic Mesic and Northern Cape York humid. There are 57 rivers that transport surface flow during rainy days.

Aquifers are present deeply into weathered rocks, fractured and weathered rocks, fine grained sediments and sand dunes. They are part of the sedimentary sequential rocks, layered sedimentary rocks or fractured basaltic rocks, fractured rocks and deeply weathered rocks. Their geological formations include alluvial sediments: shallow marine and other sediments, and layered sedimentary or fractured basaltic rocks. About 2% of rainfall will enter the groundwater system from the soil after it passes through massive soil clay and rock barriers. Some of this water will find its way to shallow or perched aquifers (10-40 m below) and much less to deep aquifers (50-500 m below). Most ground water is confined by clay and rock layers. The deep, flowing aquifers have fresh water while some shallow aquifers (including perched and basin systems) have brackish or saline waters. The demand from the coastal areas on the east is on the highest scale where the fractured aquifer productivity is low. Similarly the irrigation is highest on the eastern side of the island and partially on the west and on the north. The water demand is met from the ground, surface and integrated water supply systems. In addition to the integrated system, treated waste waters and desalinated sources are being used to meet the requirements of the capital cities. In the large inland river systems in the Murray-Darling Basin - rice, horticulture, cotton, wine, and dairy; in Queensland coastal catchments such as the Burdekin River floodplain and the black soils of the upper Fitzroy – sugar cane, cotton, grains and horticulture; in Western Australia: the Ord River and selected coastal floodplains in the north – horticulture and sugar cane; and the Swan Coastal plain and other floodplains around Perth – horticulture and dairy are predominant. The higher rainfall zones are suitable for dairying, as well as more intensive grazing enterprises that produce meat.

Drought conditions – Since 1860, the most severe droughts have occurred at intervals of 11 to 14 years. Major droughts that were recorded in the 19th century include: 1829 – Major drought in Western Australia with very little water available; 1835 and 1838 – Sydney and NSW received 25% less rain than usual and severe drought in Northam and York areas of Western Australia; 1839 – severe drought in the west and north of Spencer Gulf, South Australia; 1846 – severe drought converted the interior and far north of South Australia into an arid desert; 1849 – Sydney received about 27 inches less rain than normal; 1850 – severe drought, with big losses of livestock across inland New South Wales (NSW) and around the western rivers region; 1864-66 (and l868) – the available data indicate that this drought period was rather severe in Victoria, South Australia, New South Wales, Queensland and Western Australia; 1877 – all States affected by severe drought, with disastrous losses in Queensland. In Western Australia many native trees died, swamps dried up and crops failed; 1880 to 1886 – drought in Victoria (northern areas and Gippsland); New South Wales (mainly northern wheat belt, Northern Tablelands and south coast); Queensland (1881-86, in south-east with breaks – otherwise mainly in coastal areas, the central highlands and central interior in 1883-86); and South Australia (1884-86, mainly in agricultural areas); 1888 – extremely dry in Victoria (northern areas and Gippsland); Tasmania (1887-89 in the south); New South Wales had the driest year since records began; Queensland (1888-89) had a very severe drought, with much native scrub dying and native animals perishing; South Australia had one of its most severe droughts; and Western Australia (central agricultural areas) lost many sheep.

1902 – Severe Australian Federation Drought reduced the total sheep population to 54,000,000 from a total of 106,000,000 sheep in 1891 and cattle numbers fell by more than 40%. It was 1925 before the sheep numbers reached the hundred-million mark again. There had been a number of years of below average rainfall across most of Australia before the drought. During the drought the wheat crop was “all but lost” and the Darling River was dry at Bourke, New South Wales for over a year from April 1902 to May 1903. In the 1911-1915 period, Australia suffered a major drought which resulted in the failure of the 1914 wheat crop. During World War II, eastern Australia suffered dry conditions which lasted from 1937 through 1947 with little respite. From 1965-68 eastern Australia was again greatly affected by drought. Conditions had been dry over the centre of the continent since 1957, but spread elsewhere during the summer of 1964-65. This drought contributed to the 1967 Tasmanian fires in which 62 people died in one day and 1400 homes were lost.

The drought in 1982-83 is regarded as the worst of the twentieth century for short-term rainfall deficiencies of up to one year and their overall impact. There were severe dust storms in north-western Victoria and severe bushfires in south-east Australia in February 1983 with 75 people killed. This El-Nino related drought ended in March when a monsoon depression became an extratropical low and swept across Australia's interior and on to the south-east in mid to late March. A very severe drought occurred in the second half of 1991 which intensified in 1994 and 1995 to become the worst on record in Queensland. This drought was influenced by a strong El Nino weather pattern and associated with high temperatures in July and August 1995, the fifth continuous year of drought in parts of Queensland. In June 1994, more than 10 towns had lost irrigation systems and some areas had gone five years without decent rainfall. A part of the upper Darling River system collapsed during this drought. By October 1994, the Condamine River was exhausted, reverting to a series of ponds. Across the state more than 13,000 properties, totalling 40% of Queensland was drought declared. The flow past Goondiwindi was the lowest since 1940. Cotton farms near Moree and Narrabri had been allocated no water for irrigation which resulted in a major loss of production. The town of Warwick was particularly affected. Australia was prone to wet weather brought on by La Niña influenced weather patterns during 2000. Then from 2003 a long, severe drought, again the worst on record, was experienced in many parts of Australia. The late-winter to mid-spring rainfalls had failed in November 2006. The average rainfall in the state of South Australia was the lowest since 1900. Across Victoria and the Murray-Darling Basin the season was the second driest since 1900. The situation has been worsened by temperatures being the highest on record since the 1950s. Figure 9.3 summarizes the drought events.

The first attempt at white settlement in Victoria near Sorrento in 1803 was abandoned partly because of a lack of water and this is a reason instrumental in the development of Victoria. Melbourne was settled in 1835 at a point on the lower Yarra where a low rock ridge separated fresh water from the salty estuarine waters. The city's first water supply reservoir, Yan Yean, came on line in 1857. Major droughts experienced in Victoria and around Melbourne are 1865-66, 1914-15, 1919, 1922-23, 1938-39, 1943-45, 1967-68, 1972-73, 1976-78, 1982-83, and 1997-98. Historically, managing water demand during drought involved restrictions designed to curb use and conserve water storages. These restrictions usually limited external water use, and in some towns, street watering was banned causing huge amounts of dust to be churned up by horses, carts and carriages. In 1950, a bylaw was introduced under which any 24 hours could be declared a period of restricted water use. During these times, householders were banned from using garden hoses. Since the 1960s, water restrictions have been introduced in dry years because of low streamflow

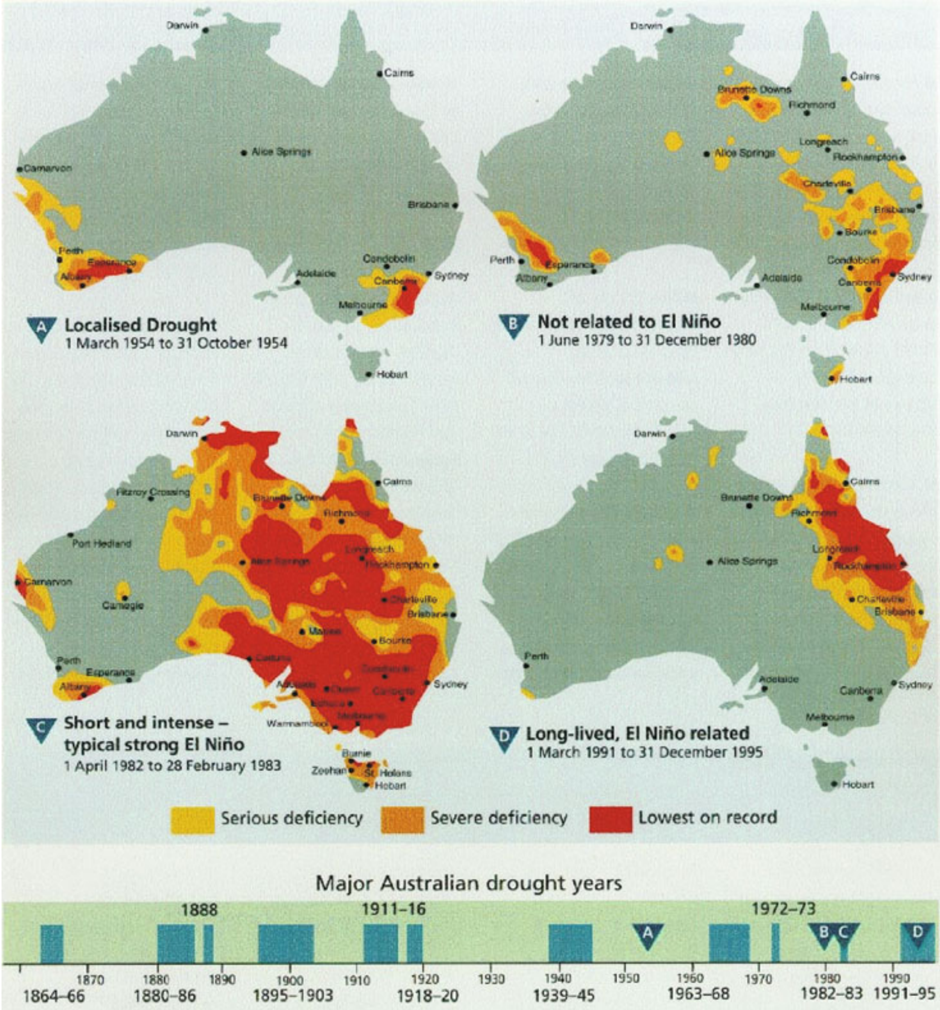


Fig. 9.3: Major drought areas in Australia – rainfall deficiency (1982-83). *Courtesy:* Government of Australia, Bureau of Meteorology

into water reservoirs resulting in low storage levels. In the severe drought of 1967-68, restrictions were introduced relating to the use of fixed sprinklers and hoses, as well as washing cars and filling swimming pools and fountains. People used buckets to water their gardens and even this practice was later restricted.

After the 1972-73 drought, water restrictions were formalised. In 1975 the Melbourne and Metropolitan Board of Works and the State Rivers and Water Supply Commission produced an eight-stage set of restrictions. In 1982-83 drought affected most of eastern Australia, and sparked the Ash Wednesday bushfires, which burnt 13,000 hectares of Melbourne's water supply catchments and caused massive dust storms. In Melbourne, Stage 6 restrictions were introduced in February 1983. Since then, Victorian water authorities have worked to plan for drought and simplify restrictions. In the early 1990s, drought-management guidelines were completed for non-metropolitan areas, and in 1995, drought response plans were completed for the newly formed metropolitan retail water companies. The plans included a four-stage restriction regime. Water storage levels have steadily declined as the current ten-year drought continues to reduce stream flow into our water reservoirs. In March 2005, the government introduced Permanent Water Saving Rules across Victoria and penalties for breaches. The rules specify manual watering systems only between 8 pm and 10 am, automatic watering systems only between 10 pm and 10 am, all hoses to have trigger nozzles, no hosing of paved areas, and apply for permission to fill a new pool.

Mitigation – Australia like many other countries relied solely on water from dams for agriculture and consumption. Drought proofing methods such as like grey-water water-recycling, government rebates for home-owners to install water tanks, and tougher restrictions on industries are also in effect. In November 2006 Perth completed a seawater desalination plant that will supply the city with 17% of its needs. Water restrictions are currently in place in many regions and cities of Australia in response to chronic shortages resulting from drought. There are presently four stages of temporary water restrictions which can be imposed by *Australian Capital Territory corporation* as shown below:

	Stage 1	*Stage 2*	*Stage 3*	*Stage 4*
Sprinklers and irrigation	Alternate days, 7-10 am and 7-10 pm	Drippers only, 7-10 am and 7-10 pm	No reticulation	
Hand-watering gardens and lawns	No restrictions	Alternate days, 7-10 am and 7-10 pm	No watering lawns; watering plants alternate days, 7-10 am and 7-10 pm	Grey water only
Swimming pools	No emptying or filling; Topping-up allowed		No topping-up, emptying or filling	
Car washing	Once a week, or at commercial car wash	Once a month, or at commercial car wash	Only at commercial car washes	No car washing
Window cleaning	Only with bucket or high-pressure, low-volume cleaner	No window cleaning		

Sydney uses the following restriction levels owing to the falling dam levels.

	Level 1	*Level 2*	*Level 3*
Sprinklers and irrigation	No sprinklers at any time; drippers only		
Hand-watering gardens and lawns:	No restrictions	Three times weekly, before 9 am or after 5 pm	Two times weekly, before 10 am or after 4 pm
Swimming pools	No restrictions	No filling pools over 10,000 L without permit	
Hard surfaces	No hosing hard surfaces (paths, driveways, cars, floors and buildings)		

Note: Falling dam levels prompted Sydney Water to impose Level 1 water restrictions on the Sydney area from 1 October 2003. When these restrictions failed to stem the reduction in the city's water supplies as a result of continuing drought, and with dam levels dropping below 50 per cent, Level 2 water restrictions were introduced from 1 June 2004. Further reductions in dam levels to below 40 per cent of capacity led to an increase to Level 3 water restrictions from 1 June 2005. Level 3 water restrictions remain in place as of February 2008; however higher dam levels may lead to reductions in water restrictions in the near future.

Adelaide and much of south-eastern South Australia takes its drinking water from the Murray River. Even lower inflows to the Murray River over the course of 2006 led to the even tougher Level 3 water restrictions being imposed on the region from 1 January 2007, which remain in place.

Recurring drought reduces agricultural production from time to time, resulting in loss of crops, downsizing of the national sheep flock and cattle herd and reduces water allocation for irrigation. Awareness of climate risk relationship between sea surface temperature in the Pacific and Indian Oceans and climate effects allows more active management of agricultural systems. Predictions may give useful guidance up to nine months in advance, but only for certain parts of Australia and depending on the time of year. Irrigated agriculture activities can face considerable risks from climate variability. Irrigated producers may actually face a higher risk of 'exposure' to failure in drought than some dry land producers, who have a number of production options available to them.

Potential negative effects of drought include reduced wheat production from reduced rainfall reliability, increasing suitability ranges for diseases and pests, reduced milk yield due to heat stress in dairy cattle, increased irrigation requirements for the sugar industry, and reduced fruit yield and quality through a reduction in chilling temperatures in some cases. *Potential positive effects include* increased plant production in northern Australia and reduced incidence of frost damage in southern Australian fruit crops. Water resource use is likely to be the key natural resource management issue directly influenced by climate change. The extent to which it is possible to mitigate the effects of extreme climatic variations, in particular drought, depends to a large extent on their predictability. In the long term, knowing the extent of climatic variability allows a rational approach to risk management.

Sustainable Australian irrigation could be achieved by:

- *Integrated catchment management* – all Australian governments recognize the interactions between landscape management, land use, on farm practice and river health, which in turn affects the quality and availability of water for water extractors and for the estuary and nearshore marine areas downstream. The irrigation industry recognizes this inter-relatedness of natural resources with many industries [e.g. cotton, dairy, rice] leading the development of industry codes of practice. Underpinning integrated catchment management is:
- *Water Accounts and Benefits* – understanding where the water, both quality and quantity, is within a catchment, how it changes with climate variability and changes in land use and practice is essential if our catchments are to yield quality and quantity water. From this water accounts base, the benefits of water use could be derived. With an understanding of the benefits, scenarios for changes in catchment management can be tested. Objectives are usually to maximise yield and quality of surface waters and ensure water balance in soils to mininise salt transport to ground water. Understanding water accounts and benefits allows managers at basin, regional and catchment scales to set:
- *Sustainable allocations* – limits are set on the volume of surface and groundwater that can be diverted for consumptive uses or stored in farm dams. This does not constrain new irrigation nor urban and industrial developments but leads to these developments being based on:
- *Water Use Efficiency* – making water available for expansion in irrigation and increased productivity through a range of on-farm and regional efficiency measures in delivery and on-farm plant use measures. These include paddock scale water use efficiency, changed varieties, varied crops, changed technology and on-farm practice, improved delivery at irrigation scheme and channel management levels and making more effective use of water available through:
- *Rapid response to climate variability* – using climate predictions, regional water managers are fine tuning delivery and annual allocations. Climate predictions before the growing season interpreted through decision support tools allow individual irrigators to optimize inputs, vary the area under cultivation and crop, and modify delivery practices and scheduling on farm. Capturing all the water available calls for:
- *Water Reuse and Recycling* – including tail water recycling on farm through to urban water treatment and reuse for high value commodities near urban

centres such as horticulture. All water used on farm, recycled or otherwise needs to be carefully managed to ensure:

- *Soil Health in-situ* – so that the soil's physical structure, chemical status and biota provide for sustainable cropping and no adverse off-farm impact, be it through excessive leakage of nutrients, recharge to ground water, build up of salts or soil erosion. Irrigators, as land and water users within a catchment, contribute to and are part of:
- *Integrated catchment management* – where this brief discussion of aspects essential for irrigation sustainability started.
- Companion Audit work on catchments, rivers and estuaries are to be carried out towards groundwater development purposes. Irrigation and its impacts are part of the contributing factors to the health of the ecosystems.

Bangladesh

It is located in the low-lying Ganges-Brahmaputra River Delta or Ganges Delta, that is formed by the confluence of the Ganges (local name Padma), Brahmaputra (Jomuna), and Meghna rivers and their respective tributaries. Most parts of Bangladesh are less than 12 metres above the sea level. Straddling the Tropic of Cancer, climate is tropical with a mild winter from October to March, a hot, humid summer from March to June. The country has a tropical monsoon climate similar to India. The cool season is from November to February, and the hot season from March until early June, when rain is usually in the form of thunderstorms. The main rainy season occurs during the southwest monsoon from June to September. Rainfall is heavy and frequent during this period. Rainfall is abundant, with most areas receiving 1500-2000 mm of rain annually. In eastern Bangladesh, rainfall is reaching up to 3500 mm. Rainfall is more regular during the southwest monsoon (June-August), and less regular when it is caused by low pressure weather systems from the Bay of Bengal during September-November.

Irrigation – Deep or shallow boreholes to draw water from underground aquifers experience hydrological drought as a result of geological changes that cut off parts of the aquifers. Fresh water resources in drought-prone areas are already declining due to over-exploitation to support irrigation in the dry months. Traditionally, rural water supply was largely based on protected ponds. There were about 1,288,222 ponds in Bangladesh having an area of 0.114 ha per pond and 21.5 pond per mauza (land unit) (BBS, 1997). About 17% of these ponds are derelict and probably dry up in the dry season. Surface water irrigation systems in the country compete for this available water in the dry season. The demand for irrigation is expected to reach 58.6% of the total supply by 2018.

Ground water – Two types of aquifers exist in Bangladesh – A shallow aquifer lies within 100 m from the surface with an overlying clay/silt blanket which is less than 2 m thick in the northwest and generally increases southward to more than 50 m. The main constituent of the aquifer materials is the medium-grained sand deposit. Ground water can be easily abstracted by installation of wells for the development of water supply systems. The water abstracted for various purposes is replenished in the monsoon. The thickness of top clay and silt layers varies between 5 and 15 m. Groundwater levels are at or near ground level during the period August-October and lowest in April-May. Ground water rises as a result of recharge during May and usually reaches its highest in late July every year. Between July and October groundwater levels are constant and maintain a balance between surface water levels and the fully recharged aquifers. Groundwater levels fall from October in response to rapid drainage of surface water and changes in base levels. The rate of fall is highest in October-November but equally large changes may take place after January when withdrawal of ground water for irrigation starts.

Drought – The two critical dry periods in Bangladesh are kharif, and rabi and pre-kharif: (1) Kharif – droughts in the period June/July to October result from dry conditions in the highland areas especially in the Barind. Shortage of rainfall affects the critical reproductive stages of *T.aman* rice (rice type), reducing its yield, particularly in those areas with low soil moisture-holding capacity. This drought also affects fisheries and other household-level activities. (2) Rabi and pre-kharif – droughts in the period January to May are due to: (i) the cumulative effect of dry days, (ii) higher temperatures during pre-kharif (>40°C in March/May), and (iii) low soil moisture. This drought affects all the rabi crops, such as boro, wheat, pulses and potatoes, and pre-kharif crops such as *T.aus*, especially where irrigation possibilities are limited. Figure 9.4 summarizes the extent of drought and severity. Like floods, Bangladesh is also vulnerable to recurrent droughts. Between 1960 and 1991, droughts occurred 19 times in Bangladesh.

Chronology of major drought events and its impact in Bangladesh

Year	*Details*
1791	Drought affected Jessore district, prices doubled or tripled
1865	Drought preceded Dhaka famine
1866	Severe drought in Bogra, rice production of the district was hit hard and prices tripled
1872	Drought in Sundarbans, crops suffered greatly from deficient rainfall
1874	Extremely low rainfall affected Bogra, great crop failure
1951	Severe drought in Northwest Bangladesh substantially reduced rice production.
1973	Drought responsible for the 1974 famine in northern Bangladesh, one of the most severe of the century.

(*Contd.*)

(*Contd.*)

Year	*Details*
1975	Drought affected 47 percent of the country and more than half of the total population.
1978-79	One of the most severe droughts in recent times with widespread damage to crops reducing rice production by about two million tonnes, directly affecting about 42 percent of the cultivated land and 44 percent of the population.
1981	Severe drought adversely affected crop production.
1982	Drought caused a loss of rice production of about 53,000 tonnes while, in the same year, flood damaged about 36,000 tonnes.
1989	Drought dried up most of the rivers in Northwest Bangladesh with dust storms in several districts, including Naogaon, Nawabganj, Nilpahamari and Thakurgaon.
1994-95	The most persistent drought in recent times, it caused immense crop damage, especially to rice and jute, the main crops of Northwest Bangladesh and to bamboo clumps, a main cash crop in the region.

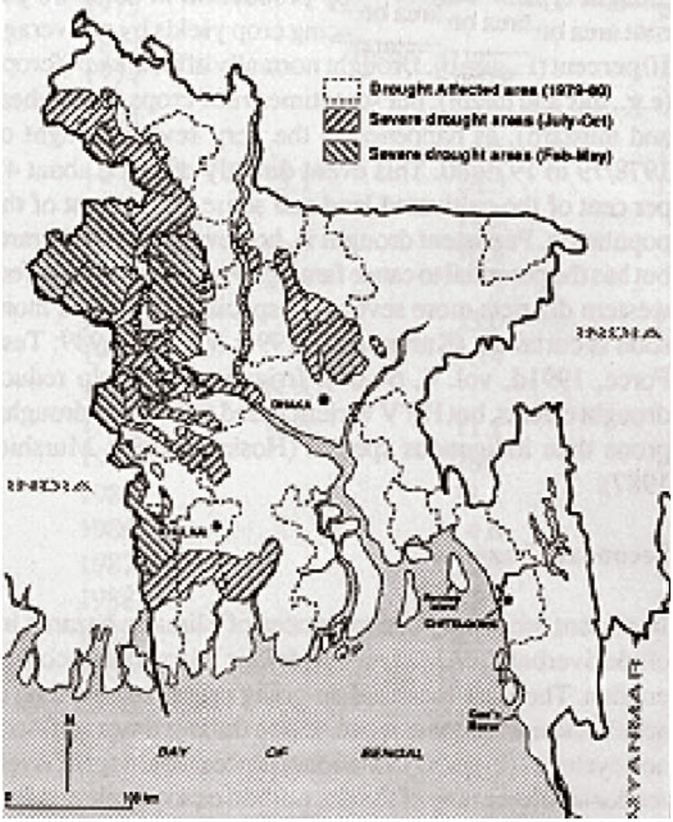


Fig. 9.4: Drought prone areas—Bangladesh.
Courtesy: Bangladesh Remote Sensing Center

Barind area has developed local thumb rules for risk. They have perceived that 12 days without rain during monsoon season in the high Barind tracts could trigger drought and in the level land Barind area, 14 days without rain could trigger drought at early stages of rice crop. Farmers in the Barind areas respond to drought based on this threshold number of dry days and their visual observations. The farmers' perception of drought is based on the length of dry spells. Crop stages in high Barind tracts are: Seedling stage: 5-7 days (mild), 7-15 (moderate), >15 (severe); Vegetative stage: 7-8 (mild), 8-18 (moderate), >18 (severe); Flowering: 5-7 (mild), 7-12 (moderate), >12 (severe). *Mitigation* – Ground irrigation through thousands of shallow and deep tube wells were provided in meeting 1970 and 1980 drought. High Yielding Variety paddy was introduced to acres of marginal and sloped lands and these lands are over-used and degraded due to human pressure. A national land use policy is sought to utilize land in judicious manner. Steps are required to develop national programmes for drought preparedness (similar to flood and cyclone preparedness). Early-warning schemes have to be undertaken to inform the population of drought-prone areas and introduce drought-relief measures for the affected people as part of the national planning strategy/national programme for drought preparedness (similar to flood and cyclone preparedness).

Iran

Iran is one of the world's most mountainous countries; its landscape is dominated by rugged mountain ranges that separate various basins or plateaux from one another. The annual precipitation ranges from 135 to 355 mm. On the northern edge of the country (the Caspian coastal plain) temperatures nearly fall below freezing and it remains humid for the rest of the year. Summer temperatures rarely exceed 29°C. A point far from altitudes can reach up to 60°C during summer. The average temperature during January and May are 22°C and 40°C respectively. It rarely snows there. The annual relative humidity is below 30%. During summer, it decreases, at times, down to 0%. It usually rains during winter and sometimes showers that leads to wash away the earth. It goes without saying that there cannot be proper and enough soil and water for plants to grow. Since these regions are always open to winds and there are not sufficient plants to preserve soil, wind erodes the earth and brings about losses. Therefore, blocking winds by wood-made walls and planting shrubs and trees are carried out to confront the destructive natural forces.

The wide range of temperature fluctuation in different parts of the country and the multiplicity of climatic zones make it possible to cultivate a diverse variety of crops. Wheat and barley are planted on dry-farmed and irrigated lands and on mountain slopes and plains. Long-grain rice of Iran grows primarily in the wet Caspian lowlands in the northern provinces of Gilan and Mazandaran, where heavy rainfall facilitates paddy cultivation. The major rivers running into the Caspian Sea in Iranian shorelines flowing from the northern Alborz altitudes are: Aras, Sefid Rud, Chalus, Haraz, Se hezar, Babol, Talar, Tajan, Gorgan, Atrak, Qarasu and Neka. Some temporary rivers either run into a body of water or get dried before reaching any watershed. Irrespective of presence of large number of rivers water has always been a vital issue. Many of the rivers contain salty water, and are seasonal that makes fresh drinkable water even more valuable.

Drought – It is estimated that 18 of the country's 28 provinces are affected by drought and majority of them are in southern, eastern and central parts. Those hardest hit include Sistan-Baluchestan, Yazd, Fars, Kohkiluyeh Boyer-ahmad, Bushehr, Hormuzgan, Kerman and Khuzestan. Although limited rainfall in late March brought some relief to crops in west-central parts, it was insufficient to improve overall prospects. The impact of drought is likely to be exacerbated by already low water reserves in dams and reservoirs, following the severe water shortage last year. Most farms in Iran are small, less than 25 acres (10 hectares) and not economically viable that has contributed to the wide-scale migration to cities. In addition to water scarcity and areas of poor soil, seed is of low quality and farming techniques are antiquated. All these factors have contributed to low crop yields and poverty in rural areas. Vulnerable groups in rural areas have limited alternative sources of income and incurred heavy losses due to crops - wheat and barley. Villagers have begun panic selling of livestock and are reportedly leaving their homes.

Jordan

Jordan consists of arid forest plateau in the east irrigated by oasis and seasonal water streams, with highland area in the west of arable land and Mediterranean evergreen forestry. The Great Rift Valley of the Jordan River separates Jordan, the west bank and Israel. The highest point in the country is Jabal Ram 1734 m above sea level, while the lowest is the Dead Sea -420 m. It is part of a region considered to be "the cradle of civilization", the Levant region of the Fertile Crescent. Climate – The western part of the country receives greater precipitation during the winter season from November to March and snowfall in Amman (756 m ~ 980 m above sea-level) and Western Heights of 500 m and the rest of the country is entirely above 300 m. The main rivers are the Jordan, the Yarmouk, and the Zarqa. The Jordan's main sources are the Hasbani River, which flows from Lebanon to Israel, the Banyas River, which flows from Syria to Israel, the Dan River, which begins and flows inside Israel, and the Yarmouk River, which begins near the Golan Heights and flows to the Jordan River. It is shared by Israel, Jordan and Syria. Most of the river's course is below sea level, following a dry, deep, rift valley called the Ghor by the Arabs. It is a relatively small river, shallow and unnavigable. Yarmuk river is the main tributary of the Jordan river and Jordan and Syria extract water from it. It supplies about 75% of the needs of the State of Jordan.

About 28,969 ha of vegetables, 131,405 ha of field crops and 54,910 ha of fruit-trees are grown here. The cultivated lands in Jordan are grouped into: *Ghor area* – Jordan Rift Valley, characterized by a subtropical climate with hot, dry summers and mild humid winters with low rainfall growing irrigated vegetables, cereals and fruit-trees comprising about 63, 14 and 23% of the planted area, respectively. Citrus and banana are the two major fruit crops; *Eastern rainfed uplands* (ERU), located on the eastern mountains and characterized by a Mediterranean climate with mild dry summers and cold rainy winters; *Side wadis* (SW), valleys which include cultivated lands located along the main tributaries descending from the mountains to the Jordan Rift Valley area. The climate is subtropical in the lower valley, but Mediterranean in the upper valley. Vegetables and fruit-trees are grown mainly under irrigation; and *Eastern irrigated uplands* (EIU), comprising certain irrigated areas alongside the desert periphery which are characterized by low rainfall (200 mm or less annually) and a continental desert climate. Jordan imports nearly two-thirds of its food requirements.

Drought – The scarcity of water is connected to meteorologic, geographic and demographic factors as rainfall is irregular in Middle East. The rainy season is short (June to August), and rainfall varies between 250-400 mm annually, which is insufficient for basic agriculture requiring at least 400 mm of regular rainfall. The availability of water is classified as very low on the Water Stress Index, which indicates the degree of water shortage or scarcity. [Water Stress Index is the value of annual rainfall divided by the total population (m^3/capita/year)]. Countries with less than 1700 m^3/capita/year are regarded as countries with "*existing stress*", while countries with less than 1000 m^3/capita/year are regarded as having "*scarcity*" and countries with less than 500 m^3/capita/year are regarded as having "*absolute scarcity*" – 167 m^3/capita/year. In 2002, the total use of water in Jordan was 809.8 million cubic metres (MCM) or 159 m^3/capita/year at the country's current population of 5.1 million people. This usage included 88.8 MCM of non-renewable groundwater (groundwater mining) and 72.4 MCM of treated wastewater.

The total renewable freshwater resources in Jordan are estimated at 850 MCM or 167 m^3/capita/year. The presence of groundwater mining and wastewater reuse (in 2002) indicates that the demand already exceeds the availability of renewable water during that year. Per capita water supply is 126.4 litre/day which is met from surface water (271 MCM); ground (473 MCM) and treated waste water (72 MCM) as on 2000. It is facing a chronic imbalance in the population-water resources equation; the total renewable freshwater resources of the country amount to an average of 775 MCM per year; the per capita of water was 160 cubic metre per annum (in 1999) and declines at a rate equal to that of population increase. An additional 143 MCM/year is estimated to be available from fossil aquifers. Brackish aquifers are not yet fully explored, but 50 MCM/year is expected to be accessible for urban uses after desalination. Despite the huge investment in the water sector, a considerable water deficit for all uses is projected at 360 MCM/year in the year 2020.

Water scarcity in Jordan is attributed to – high population growth rate including the influx of displaced persons; expansion of the cities and demand for water and sanitation services; limited renewable water resources, exacerbated by frequent drought; less than expected cost recovery for services provided; inadequate tariffs to cover real water costs particularly in the irrigation sector and excessive groundwater pumping and increased pollution. There are competing sectoral and economic interests for limited water viz. between domestic and irrigated agriculture use; the loss of biodiversity due to water scarcity and frequent drought; general social, economic and environmental impacts of degrading water quality; and less than expected efficiency of water delivery services.

Mitigation – National Water Strategy, developed and approved in 1997, states that "resource management shall continually aim at achieving the highest possible efficiency in the conveyance, distribution, application and use" of water resources. The urban water demand management policy includes – promoting a recognized industry for water efficient products; setting national product standards and information; modifying building codes to increase water use efficiency; training programme for managers and operators; a programme for peak demand reduction; national programme of audits for large consumers; arid landscaping programme; programme to promote rainwater use and a grey water reuse programme for areas with no sewerage; and a public education programme to achieve long-term awareness and change in attitudes of water users along with reduction of unaccounted water. The industrial water demand management policy includes the use of economic instruments for pollution control and technological changes and public education as a way to increase understanding about water scarcity. Comprehensive Water-Use Information Programme includes development and maintenance of a comprehensive national inventory of all water withdrawals and uses, which is essential for understanding the effects of spatial and temporal patterns of water use on the quality, availability and sustainable use of existing water resources.

The water-efficient plumbing fixtures mandated by the Jordan's Plumbing Code will reduce national water demand and wastewater flows over time due to the installation of these fixtures in new construction and also a gradual voluntary replacement of the older less efficient fixtures with the Plumbing Code-compliant models. (1) An important activity of water demand management is to promote recognized industry for water efficient products and water saving devices. (2) Updating and adjusting current building codes to increase water use efficiency is an important activity of the National water demand management programme. (3) The adoption of water-efficient appliances will also achieve savings in energy use. (4) A Plumbing Product Certification Programme through Daman at the Jordan Institute for Standards and Measures (JISM) could potentially save large quantities of water by eliminating water leakage in households if the quality of plumbing and plumbing products was improved. (5) Periodic survey of public opinion on adoption of water conservation measures will be conducted to assess and enhance the educational programme. (6) Audits of large water consumers and a public buildings efficiency improvement programme (i.e. retrofit of non-conserving plumbing fixtures in buildings), in addition to an arid landscaping programme and a best management conservation practices programme, which establishes a list of water demand management practices to be coordinated by the WDMU. On *tourist water demands* – Parallel with water audits are retrofits of hotel buildings with water saving technologies. This is important because this transition will have some cost on water users that might be prohibitive. A water demand management-training programme for all stakeholders at the water sector forms an integral part for a water demand management strategy.

Pakistan

Pakistan has a diversified landscape with high mountain ranges, rivers and plains. About 80% of the country is arid and semi-arid, nearly 12% is sub-humid and the balance 8% is humid with two distinct seasons – summer and winter. The mountains are eroded by rare but torrential desert rainstorms, but very little water ever reaches the dry basins (hamoon) between the ranges. The important rivers of Baluchistan are Zhob, Bolan and Mulla, located in the north-eastern portion. The valleys of the main streams and their tributaries exhibit similar feature and consist of flat plains of alluvial soil in the centre, with a pebbly slope of varying length rising on either sides of the mountains. It is from these pebbly beds that the supply of water for irrigation is chiefly obtained through Karezes. The country is essentially arid climate except for the southern slopes of the Himalayas where the annual rainfall varies between 760 and 1270 mm. This area has humid sub-tropical climate. In the extreme north, because of great heights, highland climate prevails. Average annual rainfall in Pakistan ranges between 250 and 800 mm. There is an extreme variation in temperature depending on the topography of the place, which experiences an overall deficiency in rainfall. It is divided into four broad temperature regions: (1) Hot summer and mild winter: 32°C or more in summer and 10-21°C in winter. (2) Warm summer and mild winter: 21-32°C in summer and 10 to 21°C in winter. (3) Warm summer and cool winter: 21-32°C in summer and 0-10°C in winter. (4) Mild summer and cool/cold winter: Summer temperature between 10 and 21°C and winter temperature between 0 and 10°C.

The major part of Pakistan experiences dry climate. Humid conditions prevail except over a small area in the north. The whole of Sindh, most of Baluchistan, the major part of the Panjab and central parts of northern areas receive less than 250 mm of rainfall in a year. Northern Sindh, southern Panjab, north-western Baluchistan and the central parts of northern areas receive less than 125 mm of rainfall. True humid conditions appear after the rainfall increases to 750 mm in plains and 625 mm in highlands. There are two sources of rainfall in Pakistan: the Monsoon and the Western Depression. The former takes place from July to September and the latter in December to March. The Dry Temperate Zone in the north of Pakistan and to the west of Baluchistan (bordering Afghanistan) are highlands and mountainous regions but do not receive even a fraction of the precipitation of what the Moist Temperate Zone or even the sub-tropical areas receive. Further, a relationship needs to be built between the altitude, temperature, and the potential evaporation: the higher the altitude, the lower the temperature and hence the evaporation. Even a small negative deviation from the low mean rainfall creates additional water scarcity in southern provinces of Baluchistan and Sindh and makes them more vulnerable to droughts.

Crops – The basic crop seasons: Winter Season and Summer Season. The winter season crops are cotton, rice, sugarcane, maize, sugar beet and gram and summer crops are: wheat, millet, sorghum, barley, tobacco, and various pulses. One fourth of the country's land area, which is not suitable for intensive agriculture, is seriously subjected to wind and water erosion, salinity/sodicity, water logging, flooding and loss of organic matter. Watersheds in upper Indus and its tributaries suffer from unfavourable soil and moisture regimes. The private tubewell growth in Pakistan is scattered across the country, inside and outside the Indus Basin. The rain-fed and un-irrigated crop belt has been converted into well-irrigated area. The use of ground water in the freshwater zone has sustained the agricultural development in the last 20 years. Fresh ground water has become important both for Sindh and Punjab. The ground water is saline in 80% of the irrigated areas of Sindh. These areas are permanently waterlogged due to ineffective drainage and high irrigation supplies. In contrast to this planned agriculture, the riverine (sailaba) area along the Indus has better perennial access to the good quality water. Over-extracting its rechargeable ground water and a depletion of aquifer is becoming irreversible in low rainfall areas in Sailaba of Sindh province. The total pumpage potential of 0.6 million tubewells installed in Punjab is higher than the canal supplies that have created an imbalance in the recharge-discharge potential. On an average, groundwater deficit is 6 to 8 maf in Punjab and groundwater depletion is occurring in the areas of high cropping intensities and the population density.

Drought has created physical water scarcity and has generated considerable stress on natural water streams (Fig. 9.5). It has a previous history of droughts but the recent droughts (1997-2001) were the longest dry spells in the last 50 years. The water stress is the maximum during Rabi season despite higher than allocated diversions during the season. Water stress is also higher in the

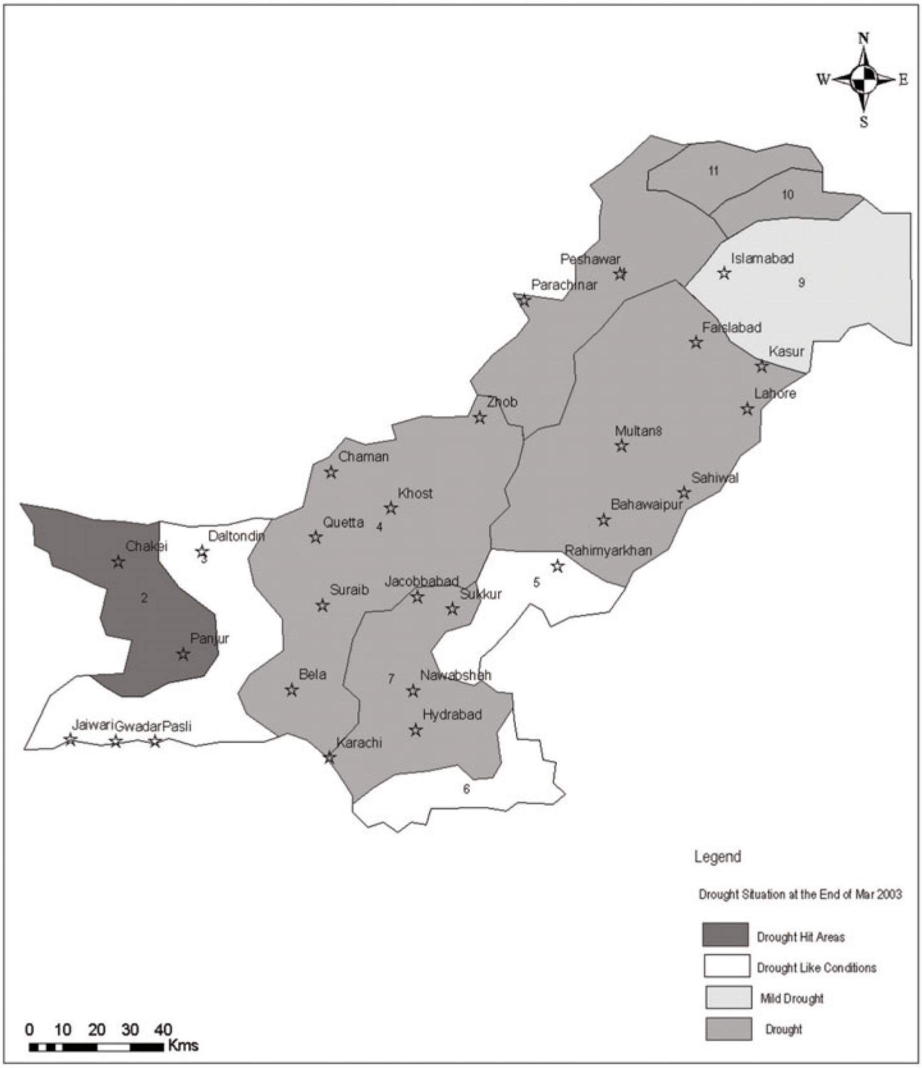


Fig. 9.5: Drought affected areas – Pakistan.
Courtesy: WMO

well irrigated areas. In the Baluchistan province, for the last four years, the monsoon rains have touched only eastern parts with limited and scattered precipitation whereas large parts of the western and central areas received no rainfall during this period. The Sindh province and rain-fed areas of Punjab suffered equally from shortage of water due to 40% lower average rainfall. The southern portion of the country such as Baluchistan, Sindh and south Punjab particularly face severe water shortage. The provinces of Baluchistan, Sindh and southern Punjab have been severely affected due to prolonged dry spell for the last three years, causing severe water shortages for human, livestock and agricultural uses. Underground water resources in western dry mountains of Baluchistan are shrinking, due to very little recharge, over-exploitation of the meagre quantity of water for horticulture and crop cultivation. Wind erosion is a common phenomenon in the deserts of Thal, Cholistan and Tharparker and along the Makran coast. According to an estimate, 3-5 million hectares are affected by wind erosion, which removes about 28% of topsoil.

9.3 Non-tropical Countries

Canada

Canada occupies a major northern portion of North America, sharing land borders with the continental United States to the south. Northern Canada includes five major physiographic regions such as Canadian Shield, Interior Plains, Arctic Lowlands, Cordillera and Innuitian Region. Annual precipitation in prairie zone ranges from 300 to 550 mm and the driest conditions in the prairies tend to be found in the south and the southwest, while the wettest areas are found in the north and northeastern prairies. Mean annual evaporation decreases from approximately 250 to 400 mm at latitude 60°N to less than 100 mm in the central portions of the Arctic Archipelago. Evaporation is greatest during the summer, especially in areas of low relief characterized by numerous bogs and lakes. Approximately two-thirds of the precipitation falls during the summer months (May to August) and a continuous snow cover lasts 4–5 months (Cohen et al., 1992).

Average winter and summer high temperatures across Canada vary depending on the location. Winters can be harsh in interior and Prairie Provinces which experience a *continental climate*, where daily average temperatures are near -15°C but can drop below -40°C with severe wind chills. In non-coastal regions, snow covers the ground almost six months of the year (more in the north). Coastal British Columbia is an exception and enjoys a temperate climate with a mild and rainy winter. On the east and west coasts, average high temperatures are generally in the low 20°C, while between the coasts the average summer high temperature ranges from 25 to 30°C with occasional extreme heat in some interior locations exceeding 40°C. It receives relatively low amounts of precipitation, particularly at very high latitudes. Annual values typically range from 100 to 200 mm over the islands of the high Arctic to nearly 450 mm in the southern Northwest Territories. Higher precipitation occurs over the east coast of Baffin Island (600 mm/a) and the Yukon, where annual amounts can range from approximately 400 to 500 mm in southeastern areas to more than 1000 mm in the extreme southwest (Phillips, 2002).

Eighteen per cent of Canada's fresh water is found in lakes (e.g. Great Bear and Great Slave lakes) on the mainland Canadian Shield of the Northwest Territories and Nunavut and not glacierzied areas. Runoff in the North is strongly influenced by snowmelt and/or glacier ablation. The dominant hydrological system in the North is the Mackenzie River, the largest river basin in Canada (1,805,200 km^2). The Yukon River drains approximately three-quarters of the Yukon as it flows northwest into Alaska. All crops grown in Canada (with the exception of greenhouse and cultured mushroom crops) and all potentially new crops are strongly constrained by climate and soil factors. Grains – wheat, barley, oats, maize (grain and silage), rye, triticale, mixed grains, canary seed, buckwheat; Oil seeds – canola, soyabean, flaxseed, mustard seed, sunflower seed and safflower; Forage and fodders – alfalfa, tame hay and fodder, forage seed; Vegetables – potato, and other vegetables excluding green house, dry legumes, lentil, dry field bean; Fruits and nuts – tree fruits and nuts, berries and grapes, tobacco, sugarbeet, sod; and other field and nursery crops are grown in British Columbia, Prairie Provinces, Ontario, Quebec and Maritime Provinces. Length of season, distribution of temperature and precipitation, soil fertility, and physical aspects of land are universal determinants of what crops can be grown.

Land use inventories that assess the suitability of land for agriculture, forestry, recreation, and wildlife have been in use for several decades. The brown soil in the semi-arid region of the Prairies varies considerably from year to year in crop yield depending on degree of drought, while dark brown soil is not as vulnerable to drought. The black soil retains moisture better than the brown soil, is rarely subject to drought, and produces higher yields. The grey soil zone has higher moisture levels, cooler temperatures, and a shorter growing season. Wheat and rye are the only grains with the potential to make raised (leavened) breads because their gluten content gives strength and elasticity to bread dough. Barley is well suited to the Canadian prairies, where most of this crop is grown, while other feed grains such as maize and sorghum are not. Barley is more resistant to drought and salinity problems.

Drought – The southern regions of the Canadian Prairies are more susceptible to drought because of their highly variable precipitation. During the past two centuries, at least 40 droughts have occurred in western Canada with multi-year episodes being observed in the 1890s, 1930s, and 1980s. Drought is a major concern in Canada but rarely has it been as serious or extensive as the 1999-2004 episode. This event produced the worst drought in over a hundred years in parts of Canada and in particular, the Canadian Prairies. Precipitation was well below normal in parts of Alberta and Saskatchewan for more than four consecutive years, extending from autumn 1999 to spring 2004. In more recent past, a major drought was recorded for the region in the 1930s. Local droughts of shorter duration have occurred since the 1930s in parts of Canada, especially in the prairies (1940s, early 1960s, late 1970s) and in Ontario (1963). In Canada the effects of droughts have been felt most severely in areas where agricultural activities allow little margin of safety in the water supply. Annual precipitation averages 380 mm, compared to 800 mm at Toronto and 1400 mm at Vancouver and Halifax.

The drought of the 1930s is of special importance because of its areal extent and severity, and because of the government policies, programmes and farming practices that resulted. The drought began in 1929 and continued, with some respites, until midsummer of 1937. Some 7.3 million ha, one-quarter of the arable land in Canada, was affected. Severe wind erosion of the topsoil compounded the effects of the drought. The drought of the 1930s brought into being federal and provincial government agencies to develop and manage drought-alleviation programmes, the most notable being the creation of the Prairie Farm Rehabilitation Administration by an Act of Parliament in 1935. The PFRA was established to help prairie farmers cope with drought by providing financial and technical assistance in the building of water-storage reservoirs such as dugouts and small dams. Agencies of the governments of Alberta, Saskatchewan and Manitoba developed programmes, alone and in combination with federal agencies, to provide facilities enabling overland pumping of water to fill small reservoirs, cattle-feed assistance, and wells and irrigation projects.

Drought has a major economic impact on the Canadian prairies owing to the vulnerability of the region's agricultural sector to weather variability. The Prairie ecozone covers an area of 520,000 km^2 across southern Manitoba, Saskatchewan, and Alberta (approximately 49–54°N latitude and 96–114°W longitude) (Raddatz, 1998). Long-lasting impacts (Fig. 9.6) include soil degradation by wind erosion and the deterioration of grasslands, which could take decades or more to recover. In May 2002, the number of recorded natural Prairie ponds was the lowest since record keeping began. In 2002, the incidence of forest fires in Alberta increased to five times the ten-year average. Between April and September 2001, at least 32 incidents of massive dust storms with associated traffic accidents were reported in Saskatchewan. The blowing dust may have been a contributing factor in two fatalities associated with these accidents.

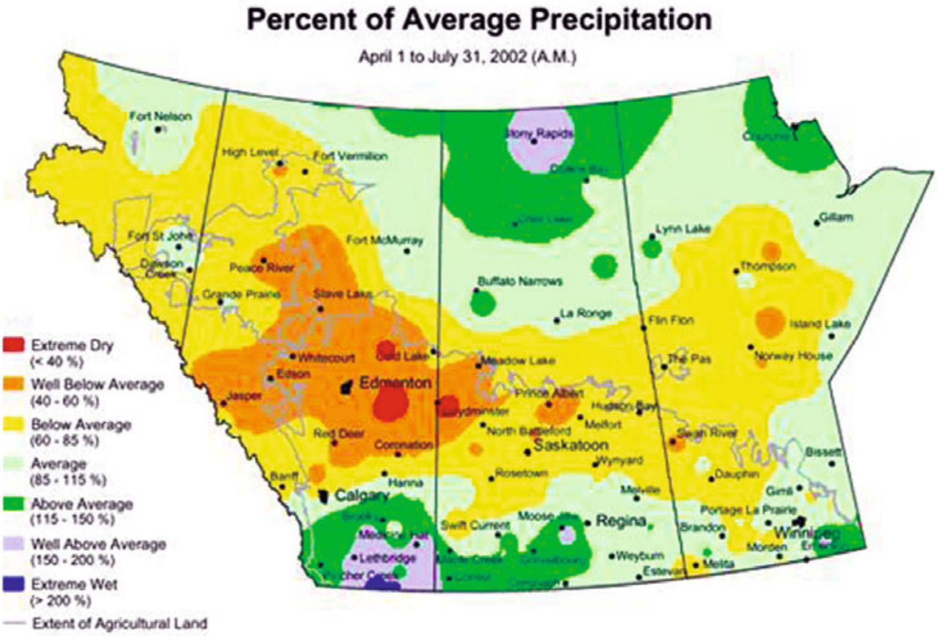


Fig. 9.6: Extent and severity of long term drought – Canada.
Courtesy: Alberta Agriculture, Food and Rural Department

China

China is one of the countries with most frequent drought, flood and water logging hazards in the world. The topography of China is characterized by high west part and low east part, gradually descending in elevation from the west towards the east to form three steps. The plains are distributed in the north to south direction, including Northeast Plain, North China Plain, Middle to Lower Yangtze Plain and Pearl River Delta Plain, being important industrial and agricultural bases and economic centres of China. Mountains account for 33.3% of the national land area, plateaus 26.0%, basins 18.8%, hills 9.9% and plains 12.0% in China. Mountains, hills and rugged plateaus, which are customarily called mountainous areas, totally account for 2/3rd of the national land area.

Climate is complex and it is subject to strong monsoon climate of the southeastern and southwestern monsoons. The northwestern part of China is arid with less than 200 mm rain per year. The central, northern and north eastern part of China has 400-600 mm rain per year of which between 70 and 90% falls in just three months during the summer. High summer temperatures throughout China contribute to high levels of evaporation. The uneven distribution of rainfall through the year and large variation year to year lead to frequent episodes of flood and drought. The precipitation varies greatly from year to year and from season to season. The average annual precipitation in China is 648 mm, or 19% less than the world average 800 mm on land, and the volume of average annual precipitation is 6190 billion m^3. The regional distribution of precipitation gradually descends in magnitude from the southeastern coastline to the northwestern hinterlands. The annual precipitation in the southeastern coastal areas and parts of the southwestern areas is more than 2000 mm, but that in the northwestern China is usually less than 200 mm, and 50 mm in the Tarim and Turpan basins in Xinjiang and Chaidamu Basin in Qinghai, etc. and even less than 25 mm at centres of those basins.

The average annual evaporation from water surface also varies greatly over regions, with the lowest value being only 400 mm, and the highest up to 2600 mm. The low values mainly occur in mountainous areas and the high ones on plains and plateaus. The average annual land evaporation also shows a trend similar to precipitation, descending in magnitude from the southeast to the northwest. It has a value of 700-800 mm in the eastern areas and usually less than 300 mm in the western areas. The northern zone (containing Beijing) has summer daytime temperatures of more than 30°C and winters of Arctic severity. The central zone (containing Shanghai) has a temperate continental climate with very hot summers and cold winters. The southern zone (containing Guangzhou) has a sub-tropical climate with very hot summers and mild winters. Due to a prolonged drought and poor agricultural practices, dust storms have become usual in the spring in China. The spring drought of winter wheat in North China; summer drought of rice in southern China; summer drought of autumn-matured crops; autumn drought of rice in southern China; drought in sowing period of winter wheat in North China and winter drought of over-winter crops in South are predominant.

It has a large number of rivers distributed such as Yangtze, Yellow, Haihe, Huaihe, Songhua-Liaohe, Pearl, Southeast Rivers, Southwest Rivers and Inland Rivers. The Songhua-Liaohe, Haihe, Yellow, Huaihe and Inland Rivers are practically situated in the northern areas of China and the Yangtze, Pearl, Southeast Rivers and Southwest Rivers in the southern areas. Most of the rivers are situated in the wet eastern monsoon climatic zone, directly flowing into the sea, with the major ones including the Yangtze, Yellow, Heilong, Pearl, Liaohe, Huaihe, Haihe, etc. Sixty to 80% of the water resources of northern China are generated in the five months between July and November and 60 to 70% of the water resources in southern river basins are generated between April and July. The river runoff varies greatly from year to year with the ratio of maximum annual runoff to minimum exceeding more than 10 in some areas. In addition, some major rivers have seen consecutive dry years and wet years.

Yellow River once saw a low flow span of 11 years from 1922 to 1932 with an average annual flow 24% less than the normal one, and also saw a wet span of nine years from 1943 to 1951 with an average annual flow 19% more than the normal one. The volume of annual river runoff in the country is 2711.5 billion m^3, equivalent to a depth of 284 mm over the whole land area. The direct recharge by precipitation accounts for about 71% of this volume, and indirect recharge by precipitation via aquifer 27% and recharge by glacier and snow melt 2%. The total volume of river runoff in the five northern river basins account for less than 20% of the national total, but the four southern river basins account for more than 80% of the national total. The river runoff is also unevenly distributed within the year. The ratio of maximum annual runoff to minimum usually has a value of less than 5 in the southern areas, but may exceed 10 in the northern areas. The intra-year variation of river runoff is also big as affected by the size of river basin as well as intra-year variation of precipitation. The rivers in the northern areas show a bigger intra-year runoff variation with the maximum runoff of consecutive four months accounting for more than 80% of the annual total in some areas, and this ratio has a value of about 60% for rivers in the southern areas. There are three major lakes – Dianchi next to Kunming in Yunnan; Chao, in Central Anhui; and Tai in southern Jiangsu.

Groundwater aquifers in China are the Paleozoic formations of China, excepting only the upper part of the carboniferous system, which are marine, while the Mesozoic and Tertiary deposits are estuarine and freshwater, or else of terrestrial origin. Groups of volcanic cones occur in the Great Plain of north China. In the Liaodong and Shandong peninsulas, there are basaltic plateaus. Trans-boundary aquifers are: Ertix River Plain (porous and shared with Kazakhstan), Tacheng Basin (porous and shared with Kazakhstan), Ili River Valley China (porous and shared with Kazakhstan), Middle Heilongjiang-Amur River Basin (porous and shared with Russia), Yalu River Valley (fractured/fissured and shared with Korea), Nu River Valley (karstic and shared with Burma), Upriver of Zuo River (karstic and shared with Vietnam) and Beilun River Basin (karstic and shared with Vietnam). Most of the ground water in mountainous areas flows out as base flow of rivers, thus overlapping with surface water resources and being mainly exploited as surface water. The degree of development percent for China is estimated to be about 47% overall and varies from 26% in the Southwest Basin to 96% in the Hai. The Northern and Southern basins are estimated to have developed about 63% and 41% of their utilizable water resources respectively. The groundwater abstraction ratio is estimated to be about 40% for entire China. The current demand for ground water is estimated to be about two-third of total available groundwater supply. The high ratio in non-process depletion includes evaporation from swamps, bare surfaces etc irrigation withdrawals (25% of return flows), flows to sink (5-10% of the return flows), evaporation from reservoir surfaces (15% of the reservoir capacity). Unsustainable of water use takes place in northern basins. The Haihe basin uses almost all of its available groundwater supply.

China's crop production deficit in 2000 was 11% of total consumption. Much of the deficit is related to oil seeds and, in the southern region, vegetables. At the same time, the southern basins have substantial rice surpluses while the northern basins have substantial wheat and maize surpluses. In some areas of the northern plain, water tables have fallen by 70 to 100 m and in some western areas by more than a hundred metres over the last decade. Where salty groundwater is used for irrigation, scarce surface water resources are also required to blend with the ground water to reduce salinity to a level where crop germination and seedling cultivation is still possible.

With most rain falling in a few summer months these areas are heavily dependent upon reservoir storage and ground water in order to provide irrigation, especially during the spring planting season (before the summer rain) and to provide consistent supplies to cities and industry. On the basis of normal demand and non-excessive extraction of ground water, China's annual shortage of water is 30-40 billion m^3. Every year, 7-20 million ha of farmland suffers from drought. Of the 669 Chinese cities, 400 suffer from insufficient water supply with 100 in severe shortage of water and affecting 160 million people. Shortage of water resources has become a heavy constraint on social and economic development in China, especially in northern China. Domestic consumption per capita is 212 l/h/d in urban areas; this compares with 150 l/h/d in UK and 427 l/h/d in United States. Water consumption in rural areas is 68 l/h/d. Among the various kinds of water uses, the rate of water consumption was 68% for agricultural irrigation. Uneven distribution of water resources i.e., precipitation is influenced by monsoon, topography, locality, etc.

Droughts are second only to floods as the natural disaster resulting in deaths in China, having claimed some 3.5 million lives since 1906. Beijing was struck by about 15 sandstorms which primarily originated from the arid and semi-arid deserts in the North-West. The death toll due to drought is dramatically reduced with national management of storage and distribution of grain. Drought occurring in China are induced by scarcity of water resources, lack of engineering projects, water pollution and mixed reasons. The impacts can be classified as droughts in agricultural areas, droughts in pastures, difficulties in drinking water in rural areas, and water shortage in urban and industrial areas. The area affected by droughts is quite large, the duration of drought is long, and the effect of droughts on agriculture is most serious. Historically, some droughts lasted several months, even several years. Droughts occurred in a consecutive period from 1959 to 1961, resulted in the average annual area of 35 million ha affecting more than 10 provinces.

In the last 50 years, 19 years suffered droughts in an area of 20% plus of the total territory (the seriously affected areas in an area of 10% plus of the total territory), spreading over 10 provinces, autonomous regions and metropolises; the probability of occurrence of drought was 38%. The probability of occurrence of drought in the Haihe River, Huaihe River and Yellow River basins is larger than that in the area along the middle and lower Yangtze River, South China, and coastal area in Southeast China.

In the areas lying to the north of the Huaihe River, spring drought, summer drought and consecutive droughts in spring and summer may occur while spring drought is the major one; in the area of the middle and lower Yangtze River summer drought and autumn drought may occur while summer drought is the major one; in South China consecutive droughts in summer and autumn may occur while the most serious droughts occur in mid-summer; in the area of the upper Yangtze River and Southwest China consecutive droughts in spring and summer may occur while spring drought is the major one. It may occur simultaneously in the Haihe River, Yellow River and Haihe River basins. The probability of simultaneous occurrence of drought in the lower Yangtze River and Southeast China is higher than the former. A close relationship of occurrence of droughts in the Huaihe River Basin and the area of the middle Yangtze River exists. 2004 was labelled as the worst in the past 50 years and was a catastrophe for Southern China. Water in hydrologic storage systems such as rivers and reservoirs are often used for multiple purposes such as flood control, irrigation, recreation, navigation, hydropower and wildlife habitat. The drought emptied reservoirs and cut power supplies. In the hardest-hit region of Guangxi Province, 1100 reservoirs went dry and hydropower generation cut dramatically. The socio-economic loss from drought was enormous.

The mighty Yellow River, tapped by factories and farmers along its 3000-mile (5000 km) course, is reduced to an intermittent stream by the time it reaches its mouth in Shandong Province. In Beijing, the water table and key reservoirs are at their lowest levels since the early 1980s. Water resources per capita are 300 cubic metres which is just 3.3 per cent of the world average in the capital city. Prolonged drought persisted in China's northern plains, with wheat one of the crops worst affected. In the northern province of Shaanxi of China, the drought affected some 667,000 hectares, 40 per cent of the province's farmland. Reduced plantings and a serious drought have led to a sharp reduction in wheat production. Severe drought in Southern China in 2006 has deprived 520,000 people short of drinking water and damaged crops. In Guangxi region (mountainous) on China's southern coast, 102,000 hectares of crops were damaged. Chongqing (on south western portion) located along the upper reaches of the Yangtze River and its neighbouring Sichuan provinces received an average of 287.1 mm of rainfall during 1st June to 14th August, which is 103 mm lesser than median. The measured temperatures were greater than 40°C for 13 days (greater than the highest record). This has affected 2.07 million hectares of farmland and accessibility to drinking water for eight million residents in the region. It is believed that the unusual drought in Chongqing and Sichuan of 2006 was one of the many footnotes of abnormal climate related to global warming (Lianyou Liu, 2007).

Yellow and Songliao basins have sufficient paddy surpluses to meet deficits in northern basins and for other crops such as wheat, maize, pulses, oil crops, and vegetables. The production deficits in these basins account for a large share of China's total production deficits and hence agricultural imports. *Drought impact on urban water supply* – Upto 2004, among 660 cities throughout the nation, there were 400 cities in the state of water shortage all over the year and 110 cities stricken by heavy water shortage, direct industrial loss was 230 billion Yuan each year. Drought impact on ecosystem – At present, 667,000 km^2 arable land and 2,350,000 km^2 pasture have degraded into mobile sandlots. Nearly 24,000 villages have been threatened by sandlots, and a great number of farmers and herdsmen have come down to "ecological refugees". Drought also caused groundwater table decline, the invasion of sea water, degradation of pastures, the dryness of reservoir, river and lakes and dust storms. The government plans to mitigate water pollution by investing in wastewater treatment facilities. Figure 9.7 shows the drought affected areas.

Drought *mitigation* approaches are: (1) Lawmaking for drought; (2) Preparedness planning for drought; (3) Chief administrator responsibility system; (4) Hydro-engineering construction – Irrigation zone construction, engineering for water storage, transfer and collection, water source reservation for drought, water transfer across watershed; (5) Using floodwater – Reservoir, flood storage and detention zone and lakes; (6) Water saving society – Agricultural techniques innovation – water saving irrigation, dryland farming, drought-resistant variety, agricultural structure adjustment, water right and water quantum system to encourage water saving, water price system to encourage water saving, economy structure adjustment – social and economy development and planning according to water resources condition; (7) Drought mitigation service network; (8) Investment system on drought reduction; (9) Drought monitoring and information management system; (10) Artificial rainfall – Application in more than 20 provinces; and (11) Research on drought mitigation – Drought monitoring and early warning. Water saving technique, preparedness planning, agricultural drought insurance system, drought risk management and water transfer across watersheds are being attempted – Transferring Yellow River water to Tianjin City; the emergency water diversion in the Pearl River basin for salt water extraction and fresh

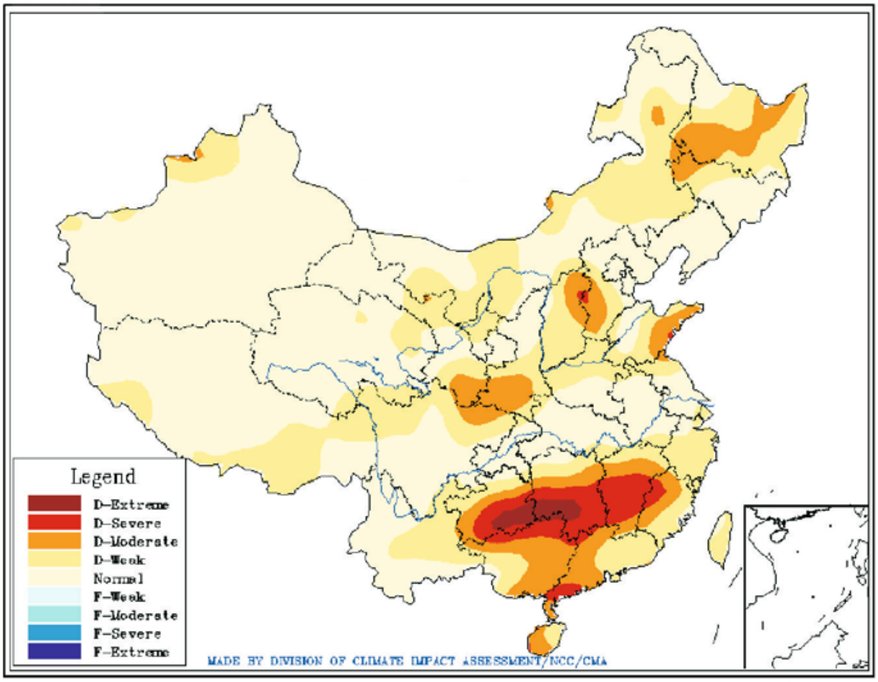


Fig. 9.7: Drought conditions in China.
Courtesy: National Climate Center of China, Meteorological Administration

water addition; Donghaiyanju water transfer; Baiyang Lake water transfer; Zhalong wetland water transfer; Beijing water transfer and South-to-north water transfer.

With respect to water, the decision objectives are: strengthening drainage basin management, defining and protecting water sources zones, defining and managing trans-provincial water pollution; planning economic development to suit water resource conditions, building water saving agriculture and investing to provide 70% wastewater treatment in urban areas by 2010. All kinds of engineering and non-engineering measures should be adopted to solve the water-shortage problem and rationally develop and utilize the local water resources. (a) The overall planning and despatching and reasonable allocation of water from rivers, lakes and reservoirs as well as ground water should be implemented; (b) The use of rain-water; for the arid and semi-arid areas, the rain-water collecting projects should be constructed to store the rain-water during the raining season for daily-life use and supplementary irrigation use; (c) Reuse of waste water. In the urban and industrial areas, the large amount of waste water should be properly treated and discharged according to the required criteria and for agricultural and environmental uses so as to make the waste water new resources;

(d) The use of light salty water; in the northern coastal areas and the northwestern inland areas, there is large amount of light salty water which can be used. According to the needs for crops and plants, the alternative use of fresh water and light salty water can help ease the situation of local fresh water shortages; (e) The use of sea water; China has a long coastal line. In the coastal areas, large amount of sea water can be used as cooling water for industries. The sea water can also be desalted to replace fresh water in order to solve the local fresh water shortage problem.

The average water use efficiency (WUE) in China is about 45%, while it is 80% in the United States of America (USA); and the average water production efficiency (WPE) in China is 1.0 kg/m^3, while it is above 2.0 kg/m^3 in the USA and Israel. The low performance of agricultural water management indicates a lack of capacity in this field. *The physical constraints* are perennial, unsteady and supplementary irrigation zones, on the basis of the annual precipitation and the requirements of the agricultural development on irrigation and drainage. The perennial (where precipitation is less than 400 mm) and unsteady irrigation zone (with over 400 mm and less than 1000 mm of annual precipitation, strongly influenced by monsoon) cover more than 60 percent of the total territory. *The competition for water for industrial and domestic uses* – The Miyun Reservoir (the biggest reservoir in North China) used to supply water for irrigation. As of 1990, it can no longer meet the farmers' needs due to the increasing industrial and domestic water demand. About 71 billion m^3 of water resources were transferred from the agricultural sector to the industrial and domestic sectors during 1980-1997.

Operation and maintenance of irrigation and drainage infrastructure – Most irrigation and drainage infrastructures in China were built during 1950s–1960s and financed by the government. Irrigation and drainage infrastructures do not receive appropriate maintenance and the situation is aggravated by the on-going institutional transition from planned economy to market economy in China. *Legislation and institutional arrangements* – Ministry of Water Resources (MWR) is charged by the responsibility for unified management of water resources. The seven major river basin commissions have the function of administering water in the relevant river basin. The local water resources authority comprises four levels i.e. the provincial, prefecture, county bureaus and the village (town) water management stations which assume the functions and responsibilities of local water administrative management within their respective jurisdictions. The management bureau (irrigation district agency) is often assigned the functions and responsibilities for water allocation and infrastructure maintenance within the irrigation district which, after buying water resources from river basin commission or local authority, sells the water to farmers.

Rehabilitation of existing agricultural water infrastructure – Agricultural water projects are poorly maintained and partly destroyed, and provide low quality service. *Reconstruction of agricultural water management institutional system* – It is time to transfer administration from government to farmers and establish a decentralized management system, of which a water user association (WUA) will be of great importance. The irrigation district agency is responsible for the operation and maintenance of main canals and main laterals. WUA, which is an autonomous corporation, buys water from the agency and sells it to farmers.

Stakeholder participation in management are: motivating all farmers to maintain and manage water projects and decreasing many redundant processes, avoiding various unreasonable burden and fees and protecting farmers' benefits; bringing down the water prices and raising water use efficiency; and ultimately, reducing dissensions on water use and promoting water management by charging according to volume of water consumption and door to door collection of fees from farmers. *Reform of water charge system* – Traditionally, the village leader or the water officer of the village committee is responsible for the village's water management system and for the collection of water fees from individual farmers. Mismanagement and asymmetric information have frequently caused much bad conduct such as open access and free-riders. From the farmers' point of view, there has been no linkage between the quality of irrigation district service and the fees paid. Indeed, high charges, low service quality and unclear management accountability have discouraged farmers from paying the charges.

Encourage crop production and enrich farmers – Low incomes from crops result in low incentives for investment in agriculture and its related issues including agricultural water management. Farmers have no money and no incentive for infrastructure construction and its proper operation and maintenance. This greatly weakens the capacity of agricultural water management. The agricultural tax exemption policy began from the northeast provinces of China in 2004, and has now been put into force in most provinces. Planted areas are protected to guarantee output; the direct subsidy system is completed to financially support farmers and agricultural production; and a compensation mechanism is established to reimburse grain production regions. More financial expenditure has been allocated to irrigation construction and other public projects in grain production areas through irrigation area rehabilitation project. *Promote the establishment of water rights and water market* – Due to the lower margin price of agricultural water, it is often transferred to the industrial and domestic sectors. There is no appropriate water right system in China, so agricultural water is often transferred without any fee. They need to be vested with clear water rights to give the right incentives for improvement of the irrigation system. Capacity development and water market can promote each other.

Due to large-scale development and utilization of water resources along the river, the conflict between water supply and demand along the Yellow river has been intensified since the 1990s. Meanwhile, the lower reaches of the Yellow River tended to dry up more frequently. It was the worst in 1997 when the Yellow River did not reach the sea for 226 days.

Southern China is abundant in water while northern China is short of water. The South-to-North Water Transfer Project is an important infrastructure aimed at promoting optimum allocation of water resources nationwide. The project will transfer water from the lower, middle and upper reaches of the Yangtze River, forming three routes of water transfer, namely the East Route, the Middle Route, and the West Route. Connecting the four major rivers i.e. the Yangtze River, the Yellow River, the Huai River and the Hai River, the project will form an overall pattern of water resource allocation characterized by "four latitudinal rivers and three longitudinal rivers", making it easier to allocate water across the country. The Project for Integrated Management of the Tarim River Basin and the Heihe River Basin was launched to transfer and divert water to the lower reaches that are deteriorating in ecological environment. The Tarim River, the largest inland river in China, gets water again after more than 20 years of drying-up in its 363 km-long lower channel, bringing life to the dying vegetation of the desert. The Green Corridor regained its vitality. Remarkable improvement was also achieved in the ecology in the lower reach of Heihe River, the second largest inland river of the country.

European Union

Member countries of the European Union is grouped into southern countries (Bulgaria, Cyprus, France, Greece, Italy, Malta and Spain); western and central countries (Austria, Belgium, Denmark, France, Germany, Ireland, Luxembourg, Netherlands, Portugal, and United Kingdom); Nordic countries (Finland and Sweden) and eastern countries (Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Slovenia, and Slovakia). About 18% of the total water abstraction in EU is used for public water supply, 24% for agriculture, 14% for industry and 44% for energy production. *Climate* – Mean annual precipitation is likely to decrease over much of Europe (particularly in Southern and Central Europe). Changes in extremes are likely to be more dramatic than in the means. A joint effect of a temperature and drop in precipitation (drop number of precipitation days) is foreseen for the summer and this is likely to result in an increase in drought severity and frequency. Cyprus has a semi-arid climate and limited water resources which almost entirely depend on rainfall that is highly variable with considerable regional variations. 2, 3 or 6 consecutive dry years are observed. It has small catchments that do not provide any perennial flows. High air temperatures in summer, when associated with clear skies and sunshine increase the evapotranspiration to the extent that little or no rainfall is available for ground water or river recharge and also aggravate the severity and duration of drought events. Winter droughts are caused by precipitation being stored in the catchment in the form of snow and ice preventing any recharge of rivers or aquifers until air temperatures rise again and snow melting starts. Delay in the start of the rainy season, occurrence of rains in relation to principal growth stage and the effectiveness of the precipitation (intensity and number of events) also cause drought situation. High wind velocities and low relative air humidity are often associated with a drought event in many regions of the world and can significantly aggravate its severity.

Water extraction of the western and central countries, 42% (106,138 Mio m^3) of the total water abstractions, is followed by southern countries 40% (99,506 Mio m^3), eastern countries 16% (38,769 Mio m^3) and Nordic countries 2% (5662 Mio m^3). 50% of the abstracted water is used for agriculture by southern countries whereas western countries use 56% for energy production. 13% of water consumed by EU is used for public water supply, 69% for agriculture, 10% for industry and 8% for energy production. Southern countries consume 65% (43,327 Mio m^3) of the total EU consumption followed by west and central 23% (15,673 Mio m^3), eastern countries 10% (6558 Mio m^3) and Nordic countries 1% (196 Mio m^3). Tourism activity along the Mediterranean coast reaches upto 2300 people/km^2 during the summer and the consumption increases accordingly. Water availability per capita and the country is the lowest for Malta and Cyprus – <500 m^3/capita/year. The role of irrigation differs between countries and regions because of climatic conditions. It is an essential element of agricultural production and cultivable areas are irrigated throughout the growing season each year in Southern countries. Maize is the major crop in Greece (80%), Spain (72%), Italy (60%) and Portugal (59%) that requires irrigation support. Irrigation is generally used to improve production in summers in Central and Northern countries. Water allocation rate decreased slightly from 6578 to 5500 m^3 per hectare per year between 1990 and 2000.

Droughts in Europe are not rare. Whilst a severe water shortage at specific location is expected once every 50 years, scarcely five years go by without a shortage across at least some part of Europe and some of these events can last for several years. The major impacts of recent events are: *1973* Austria, Germany + former Czechoslovakia – Very dry winter/spring resulting in low snow-melt and subsequent water shortages; *1976* Northern Europe (Scandinavia to France) – Unprecedented 16-month duration in UK led to massive subsidence claims as building foundations failed. French milk yields were reduced by 25%; *1984* North and west UK – Very dry spring and summer led to the imposition of hose pipe bans; *1988-92* Most of Europe – Anomalous circulation pattern caused rainfall deficits over a large area interspersed with short wet periods causing large scale subsidence; *1992* Germany, Hungary, Bulgaria and much of western Russia – German crop production reduced by 22%. Irrigation suspended in Bulgaria. Worst Russian drought in 10 years. *1990-95* Spain and Portugal – Prolonged drought across the entire Iberian peninsula. Water supplies in Seville were cut for upto 12 hours per day during 92-93. Hydroelectric power suspended 94-95. *1995* Ireland, UK, Norway and Sweden – Agricultural losses in the UK were valued at £180 m. Reductions in Norwegian hydropower capacity led to 600% increase in mean weekly prices; *1999* Finland – Hot dry summer resulted in very low water levels in rivers and groundwater; *2003* Much of continental Europe – Many deaths from unusually prolonged high temperatures. Forest fires, subsidence, power cuts and agricultural losses.

Droughts and long dry periods have led to serious power failures in Europe and in consequence to great economic losses in the industrial sector and tourism. Meanwhile most drought assessments concentrate on the effect on the vegetation and estimate economical losses of agricultural production. The drought risk should also take the effects on the producing industry and the service sector into account. The European countries' agricultural GDP share is well below 5%, in most of the countries it is less than 3%. Therefore in Europe drought impacts on the industry and service sector are more harmful to the economy than agricultural losses. The 2003 drought in Europe accounted for almost 1/3 of the economic natural hazard losses (Munich Re, 2004). The long-term drought effect on groundwater and surface water levels has a strong impact on, e.g. power production. Nuclear power plants, for example, might have to run on lower production rates because their cooling systems depend on rivers or lakes. Most of the hydropower plants in areas affected by droughts suffer from reduced energy production due to lower water levels; this is especially crucial for an economy in a country like Norway that is depending on hydropower. Other countries in northern Europe that have a high consumption of hydropower also experience the economical effects of rising electricity prices during droughts.

Additionally, power plants might have to shut down because the cooling water taken from lakes, rivers or the sea might be too warm to be used. Meanwhile failing groundwater recharge in a certain period does not necessarily have long lasting ecological effects; an accumulation of many events over several years can affect the entire ecological system. It is also important, for instance, to take the dependency of a groundwater system on annual recharges into account. Regions with very shallow aquifers require a steady recharge meanwhile deeper and larger aquifers can cope easier with drier years, simply because they store much more water. In Europe the man-made impact on droughts is considerable. There are several examples of water resource mismanagement, such as over-pumping of aquifers, sealing of areas increasing surface runoff and restricting groundwater recharge, overuse of water in dry areas and intensive agriculture, and many more. Since climate conditions that lead to droughts are extremely difficult to predict and they are usually not recognizable until they are already well advanced, the drought hazard can only be managed by the sustainable use of water resources. Water should be stored in times when it is abundantly available in order to ensure enough supply during a drought.

Norway has problems with water deficiency because the country's economy is strongly depending on hydropower. Even though Norway has some of the rainiest places in Europe small negative deviations in precipitation can lead to energy problems because the water reservoirs are not refilled appropriately. Meanwhile Portugal and western Spain have the largest drought potential in Europe, eastern Spain appears to have generally a lower potential than central Europe. Some areas in southern Europe that are usually associated with droughts appear less dramatic in this map. The reason for this lies in stronger local effects of agricultural droughts, as these might partly be related to the adequacy of agricultural systems and related water scarcity. Also southern Italy appears to have a low drought potential, even though it is surrounded by areas with a higher drought potential. Southern Italy is not directly related to precipitation deficits but to other reasons not displayed here.

Austria, Belgium, Cyprus, France, Hungary, Italy, Lithunia, Malta, the Netherlands, Norway, Portugal, Spain and United Kingdom have been affected by droughts in the last thirty years (1976-2006) with different degrees of intensity; Italy, Portugal, Cyprus, and Spain have registered 8 to 21 events while large parts of the Cyprus, Finland, France, Italy, Malta, Portugal and Spain are frequently affected. Drought is predominant for one month in Hungary, Germany and Lithunia and two to six months in Austria, Belgium and France.16 countries are considered as non-water stressed based on Water Exploitation Index (indicates the nation as a whole). Bulgaria and Romania have low WEI (10-20%) while Cyprus, Italy, Malta and Spain are water stressed (WEI >20%). South East and Thames River basin districts of England are affected by water scarcity. Western parts of Flanders of Belgium experience water stress due to the imbalance between pumped amount of ground water and the limited recharge through the thick clay layers. This has locally caused a great decline in piezometric heads in the aquifer of the Createaceous layers and Landenian sands. Groundwater levels dropping up to 165 m were observed. Denmark's groundwater abstraction exceeds sustainable recharge by upto 300% around Copenhagen and large towns and irrigation is dominant in Western Jutland and exceeds sustainable recharge by upto 70%. Eastern part of Slovakia has problem with ground water and it is tackled by ensuring drinking water from surface water reservoirs. Over-exploitation of ground water occurs in Cyprus (13 groundwater bodies – 68% are at risk from over-pumping). 30% of groundwater bodies are at risk as a result of groundwater abstractions attributed to – public sources providing ground water for the municipal supply; abstraction sources utilized by the private sector and low yield shallow wells utilized for secondary domestic purposes. Groundwater abstraction is important in three river basin districts (30%). Some of the water bodies classified at doubt are significantly impacted by water abstraction.

Desalination has been introduced in Cyprus to increase water security at one unit in 1997 at a production capacity of 40,000 m^3/day and second in 2001 at a production capacity of 51,667 m^3/day that has led to higher energy consumption (8% of total electricity consumption). Coastal areas and islands are the most exposed to interruption in water supply. Farmers bear high water costs due to deeper groundwater pumping and insufficient surface water resources leading to income losses and decrease in agricultural competitiveness. In Spain impact of costs on energy production and agriculture is significant leading to re-conversion of irrigated lands due to water scarcity. Water prices for households have increased by 30% in Segura basin. Agricultural margins are reducing and a greater uncertainty is being put on production leading to loss of competition. Water deficiency in Italy may lead to difficulties in drinking water supply and also on tourism. Agriculture is affected in eastern parts of Germany. The Netherland incurs 25 millions Euro per year for tourism, 600 millions Euro per year for agriculture and 72 millions Euro per year for inland navigation. Water prices are increased in South East and Thames river basin districts in England to ensure security of supply. Industry, energy and agriculture sectors are obliged to invest in water efficient technology and water harvesting/alternative supply sources. In Finland, water supplies provide 50 lts per inhabitant per day in a situation where the main water intake is out of use.

Over-pumping from ground water to meet water demand resulted in the depletion of all aquifers and sea water intrusion in many coastal aquifers in Cyprus. Saltwater marine intrusion is taking place at over-exploited Segura basin in Spain. 80% of the exploited water is fed to irrigation needs. Reduction of water flows and storage lead to rising pollutant concentration in water bodies and, therefore, water quality deterioration and minimum flow requirement of ecosystems are not guaranteed in Italy. Loss of natural value may be noted, as it is influenced by the amount of water, seepage level, quantity of salt in ground water and surface water as well as the features of water coming from outside the area is seen in the Netherlands. Unsustainable abstractions have caused low river flows, poor quality and loss of wildlife including fish, in addition to shrinkage of aquifers and low groundwater levels in South East and Thames river basin districts in England.

Mitigation – Demand side measures were taken by the member countries such as: reduction of leakages (10-20%) in the distribution networks in *Sweden*; regulatory target for leakage reduction based on economic principles in *England and Wales*; water savings – appliance design and efficient building standards to enhance the number of low water consumption installations by *Germany*; a law banning the use of hosepipes for car washing or pavements and subsidies for water reuse in *Cyprus*; new technologies and changing processes in industry and agriculture to get wise use of water; natural storage improvement, improvement of irrigation technology, optimizing soil water utilization and irrigation and improving agriculture management to reduce water consumption; moving from public supports for irrigation development to public supports directly aimed at improving existing infrastructures and lowering agricultural uses (reduction in water consumption per ha or irrigated areas); promotion of improved waste water reuse where appropriate (projects underway in Barcelona and other towns in *Spain* and recycled water for irrigation and groundwater recharge in Cyprus); setting up water banks and quota systems (quota system and penalty charges for over-consumption in Cyprus and emergency legislation in improving irrigation networks in Spain); setting-up adapted pricing policies (French draft water law – water use fee based on volume abstracted over the year, cost of possible substitution reservoirs borne by all agricultural water abstractors in the affected river basin); and awareness campaigns.

The following *water pricing system* is followed: *Austria* – drinking water charge, waste water fee, no pollution charges, no resource costs to any user for taking surface or groundwater, sewerage and waste water charges; *Belgium* – abstraction charge, waste water charges; *Finland* – drinking water charge, waste water charge; France – pollution levy, withdrawal levy, taxes on water used; *Germany* – surface water abstraction charges, waste water charge; *Greece* – waste water charge with sanitation fee; *Hungary* – drinking water charges, water and sewerage charges; *Italy* – waste water tax, tax on polluted discharges into the environment; *Malta* – sanitation fee; *Portugal* – drinking water charge; *Slovenia* – drinking water charge, water pollution fees, general tax for water pollution; *Spain* – water pollution fee on discharges into rivers; waste water charges, municipal sewage service charge, drinking water charge; *Sweden* – tax for collection and treatment of waste water.

Agriculture water tariffs are based on – pricing method by land area (based on irrigated area and crop area segmentation); metered pricing – (usage volume or time-based calculation); dual pricing – block rate pricing and different prices for different users; improved charged pricing – fees based on agriculture land and irrigation that are on the increase; incentive metered pricing – fees are charged for exceeding a given volume of water and incentives provided for conservation; passive water intake – a balance in overall water supply and demand in an irrigation district and farming families use the water freely according to the needs, total water usage rights of the family (if water is conserved rebates are paid) and water market pricing method (price is set by voluntary payments for marginal water volume units of farming families). *Supply side measures* – preservation of the functioning of natural catchments and aquifers by way of possible design adapted agro-environmental measures and focus them on drought areas; improvement of the efficiency in the use of existing water infrastructures and water recharge aquifers.

United States of America

Geomorphic or physiographic regions are broad-scale subdivisions that are based on terrain texture, rock type, and geologic structure and history. Nevin Fenneman's (1946) three-tiered classification of the United States - by *division, province*, and *section* – has provided an enduring spatial organization for the great variety of physical features. Rainfall climatology differ significantly across the United States. Late summer and fall extratropical cyclones bring a majority of the precipitation which falls across western, southern, and southeast Alaska annually. During the fall, winter, and spring, Pacific storm systems bring precipitation to most of Hawaii and the western United States. Lake-effect snows add to precipitation potential of the Great Lakes, as well as Great Salt Lake and the Finger Lakes during the cold season. The El Niño-Southern Oscillation affects the precipitation distribution, by altering rainfall patterns across the West, Midwest, the Southeast, and throughout the tropics.

During the summer, the Southwest monsoon combined with Gulf of California and Gulf of Mexico moisture moving around the subtropical ridge in the Atlantic ocean bring the promise of afternoon and evening thunderstorms to the southern tier of the country as well as the Great Plains. Equatorward of the subtropical ridge, tropical cyclones enhance precipitation across southern and eastern sections of the country, as well as Puerto Rico, the United States Virgin Islands, the Northern Mariana Islands, Guam, and American Samoa. The jet stream brings a maximum summer precipitation to the Great Lakes. Large thunderstorm areas known as mesoscale convective complexes move through the Plains, Midwest, and Great Lakes during the warm season, contributing upto 10% of the annual precipitation in the region. The eastern half of the contiguous United States east of the 98th meridian, the mountains of the Pacific northwest, and the Sierra Nevada range are the wetter portions of the nation, with average rainfall exceeding 30 inches (760 mm) per year. The drier areas are the Desert Southwest, Great Basin, valleys of northeast Arizona, eastern Utah, central Wyoming, and the Willamette Valley. Increased warming within urban heat islands leads to an increase in rainfall downwind of cities.

The two patterns of rainfall which stand out are: the gradual transitions east of the eastern flanks of the Rockies, versus the heterogeneity in the West. In the West the rainfall patterns are strongly controlled by topography and proximity to the Pacific Ocean. Places east of an N-S oriented mountain range, such as the Cascades of Washington and Oregon, are dry, drier than places at the same elevation on the west side of the same mountain range. A second pattern dividing east from west is that in the East, it tends to be wetter to the south, where warmer air holds more water vapour, which largely originates over the Gulf of Mexico. In the West, it is wetter to the north, as most frontal systems stay north, especially in summer. Precipitation increased by about 10% since 1910. Both the rainfall frequency and intensity have increased. There are six more days with rain each year since 1910, on average, and there are more days with heavy rainfall, e.g. over 2" (50.8 mm/ day).

The percentage of total rainfall contributed by falls within the top 10 percentile has increased from 36% to 40%. The median rainfall shows no trend, on the whole. There appears to have been cycles of about 20 years and 12 years in the annual rainfalls in five states in the Midwestern USA over the past century. The minima correspond to times of drought in the 1910's, 1930's, 1950's and late 1970's. These interdecadal rhythms seem limited to the Midwest and central plains, and not to be present in the eastern and northern parts of the contiguous US. The quasi-12-year cycle is not evident in most of Nebraska. A reduction in the amplitude of the 20-year cycle since about 1965 has been accompanied by an increase of the 12-year cycle, with an overall increase of annual rainfall. It is suggested that the changes are due to alterations in sea-surface temperature and sea-level pressure in the north Atlantic, which have the same periodicities and relate to the intensity of the Bermuda high, i.e. the North Atlantic Oscillation. This anticyclone controls a low-level jet across the plains which bring moisture there.

River – Missouri, Mississippi, Yukon, Rio Grande, St. Lawrence, Arkansas, Colorado, Red, Brazos, Columbia, Snake, Platte, Ohio, Pecos, Canadian, Tennessee, Colorado, North Canadian, Mobile, Kansas, Kuskokwim, Green, James, Yellowstone, Tanana, Gila, Milk, Quachita, etc. are some of the rivers which flow within the territory and Alsek River (Canada), Columbia river (Canada), Okanagan (Canada), Kettle (Canada), Kootenay (Canada), Skagit (Canada) and Yukon (Canada) are flow-out/in-coming rivers.

Major Crops Grown - corn grown on over 400,000 farms and 80% of all US corn is consumed by domestic and overseas livestock, poultry, and fish production. 73 million acres of cropland produce soybeans which accounts for over 50% of the world's soybean production. Hay-Alfalfa crop grown is mainly for domestic consumption. About two-thirds of total U.S. wheat production comes from the Great Plains (from Texas to Montana). Wheat is classified by time of year planted, hardness, and colour (e.g. Hard Red Winter (HRW)). 32,000 farms produce over 20% of the world's cotton grown from coast-to-coast, but in only 17 southern states. Grain sorghum, primarily used as an animal feed, but is also used in food products and as an industrial feedstock is grown in Kansas, Texas, Nebraska, Oklahoma, and Missouri that accounts for 70% to 80% produce of world sorghum exports. 9000 farms produce rice in Arkansas, California, Louisiana, Mississippi, Missouri, and Texas that account 1% of the world's total.

Groundwater system in the United States is unique in terms of climate, hydrogeologic framework, and boundary conditions (both type and location), and they respond differently to stress. Thus, the sources of water (that is, the location and magnitudes of changes in inflows, outflows, and storage) that supply withdrawals from major aquifer systems in the United States are highly variable. Biscayne Aquifer, Bruceian Aquifer, Edwards Aquifer, Floridan Aquifer, Great Miami Aquifer, Kirkwood-Cohansey Aquifer, Lloyd Aquifer, Mahomet Aquifer, Ogallala Aquifer, (also known as the High Plains Aquifer), Ozark Plateau Aquifer, San Diego Formation, Sankoty Aquifer, Snake River Aquifer and Spokane Valley-Rathdrum Prarie Aquifer are some of the significant aquifers.

Ogallala aquifer is one of the world's great aquifers, but in places it is being rapidly depleted by growing municipal use, and continuing agricultural use. It underlies portions of eight states, contains primarily fossil water from the time of the last glaciation. Annual recharge, in the more arid portions of the aquifer, is estimated to total only about 10% of annual withdrawals. *Kirkwood-Cohansey aquifer* located under the Pine Barrens (New Jersey) of Southern New Jersey, contains 17 trillion US gallons (64 km^3) of purest water. *Mahomet aquifer* supplies water to some 800,000 people in central Illinois and contains approximately four trillion US gallons (15 km^3) of water. *Spokane Valley-Rathdrum Prairie aquifer* covers 842 km^2 in Eastern Washington and Idaho provides drinking water for 400,000 people. *San Diego formation* is a water aquifer for San Diego, California and Los Angeles, California. The *Snake River Plain aquifer* in Idaho provides extensive water for irrigation as well as much of the flow of the Snake River through springs. Prior to about 1960, surface-water irrigation raised water levels in parts of the Snake River Plain aquifer by 60-70 ft and increased groundwater discharge to the river and springs.

The aquifers of the Atlantic Coastal Region generally are confined aquifers, with productive units commonly overlying one another. This increase in groundwater use from the *Floridan, Northern Atlantic Coastal Plain, and Southeastern Coastal Plain aquifer* systems have resulted in a significant expansion of the areas affected by groundwater declines since the 1983 compilation. Groundwater level declines in basin and range aquifers in California, Arizona, Nevada, and Utah and become observable when examining the declines from individual wells. Groundwater use from basin and range aquifers is the fourth highest among the nation's principal aquifers. Groundwater use in the Mississippi River Valley alluvium, the Coastal lowlands, and the *Mississippi embayment aquifer systems* have been fundamental to the region's agriculture, industry, and some municipalities. In the Houston, Texas area, extensive pumpage of ground water to support economic and population growth has caused water-level declines of approximately 400 ft, resulting in extensive land-surface subsidence of as much as 10 ft. Regional Aquifer-System Analysis (RASA) programme of USGS monitors the water level from select aquifers.

Drought – Cook and Krusic (2004) presented the multi-year drought in the western USA and indicated that Medieval Mega drought occurred from 900 to 1300AD. This reconstruction shows an abrupt shift to wetter conditions after 1300 AD coinciding with Little Ice Age. Studies are indicating that the United States had other droughts between the 1700s and 1910s. The USA experienced three major multi-year droughts during the latter half of the nineteenth century: 1856-1865, 1870-1877 and 1890-1896. Historical events were based on early instrumental data and an extensive network of gridded tree-ring data have been used to identify the existence, extent and severity of these events. These events devastated the small, self-dependent and often isolated farming communities in the area at the time. The 1856-1865 'Civil War' drought had a profound ecological and cultural impact on the interior USA, with the persistence and severity of drought conditions in the Plains surpassing those of the infamous 1930s Dust Bowl area drought (known as the Great American Desert).

The storms of the Dust Bowl were given names such as Black Blizzard and Black Roller because visibility was reduced to a few feet (around a metre) and led to an ecological and human disaster. The Dust Bowl of the 1930s is represented as a period for heavy drought across many states. 1934, 1936 and 1939 were extremely hot and dry years across the United States, that led to death of many people, livestock and animals. The Dust Bowl area is characterized by plains which vary from rolling in the north to flat in the Llano Estacado. The area is semi-arid, receiving less than 510 mm of rain annually that supports the short grass prairie *biome* originally present in the area. During wet years, the rich soil provides bountiful agricultural output, but crops fail during dry years. This region is subject to winds higher than any region except coastal regions. 100°F temperature and dust storms would be very common for people residing in northeastern United States.

During the 1950s, the Great Plains and the southwestern U.S. withstood a five-year drought, and in three of these years, drought conditions stretched coast to coast. The drought was first felt in the southwestern U.S. in 1950 and spread to Oklahoma, Kansas and Nebraska by 1953. By 1954, the drought encompassed a ten-state area reaching from the mid-west to the Great Plains, and southward into New Mexico. The area from the Texas panhandle to central and eastern Colorado, western Kansas and central Nebraska experienced severe drought conditions. The drought maintained a stronghold in the Great Plains, reaching a peak in 1956. The drought subsided in most areas with the spring rains of 1957. The 1950s drought was characterized by both low rainfall amounts and excessively high temperatures. Texas rainfall dropped by 40% between 1949-1951 and by 1953, 75% of Texas recorded below normal rainfall amounts. Excessive temperatures heated up cities like Dallas where temperatures exceeded 100°F on 52 days in the summer of 1953. Kansas experienced severe drought conditions during much of the five-year period, and recorded a negative Palmer Drought Severity Index from 1952 until March 1957, reaching a record low in September of 1956.

One exceptional and really devastating drought was during 1988 and 1989. Following a lighter drought in the southeastern United States and California the previous year, this drought spread from the mid-Atlantic, Southeast, Midwest, northern Great Plains and western United States. This drought was widespread, unusually intense and accompanied by heat waves which killed around 4800 to 17,000 people across the United States and also killed many livestock, hens, cattle, horses, farm animals and other animals across the United States. 1988 drought destroyed crops nationwide, residents' lawns went brown and water restrictions hit many cities. The Yellowstone National Park fell victim to wildfires that burned many trees and created exceptional destruction in the area. Mississippi River levels were lower than normal during 1988 because of the conditions affecting the Upper Midwest. During 1999, the Northeast, including Kentucky, New York, New Jersey, Pennsylvania and Maryland were pummeled by extensive heat waves which killed almost 700 people across the northeastern US. North American droughts are linked to the global climate system, linked to both oscillations in the Pacific and the Atlantic Oceans.

When the Atlantic Ocean is cooler this typically corresponds to wetter conditions in the American west, while a warmer Atlantic corresponds to drought and decreased water flow in the West. Changes in the Atlantic (as measured by the AMO) interact with the PDO (ENSO, oscillations in the Pacific between El Nino and La Nina conditions) to affect climatic conditions on the North American continent in a complex pattern that is hard to predict and not fully understood. The recent drought, referred to here as the early 21st century drought, has its origins in several global-scale atmospheric and oceanic processes that reduce delivery of atmospheric moisture to the Colorado River basin. ENSO reflects an oscillation between two basic states of the ocean. The warm phase (negative SOI), called the El Niño, involves warming of the eastern tropical Pacific Ocean off the coast of Peru. The warm water spreads northward in the eastern North Pacific Ocean off the west coast of the United States. The cold phase (positive SOI), called La Niña, is the opposite, resulting in a cooling of the water off western North America.

Tree-ring reconstructions of Colorado River flows provide a longer-term flow record that can be used to assess drought frequency. One of the most important conclusions from dendrochronology is that the period from 1906 through 1930, which was partially used to determine flow allocations under the Colorado River Compact, was likely the highest period of runoff in 450 years. The biggest drought we find in the entire record was in the mid-1100s. It was surprising that the drought was as deep and as long as it was. Colorado River flow was below normal for 13 consecutive years in one interval of the megadrought, which spanned 1118 to 1179. Meko contrasted that with the last 100 years, during which tree-ring reconstructed flows for the upper basin show a maximum of five consecutive years of below-normal flows. The Colorado supplies water for cities and agriculture in seven western states in the U.S. and two states in northwestern Mexico. Los Angeles, Las Vegas, Denver, Phoenix, Tucson and Albuquerque are among the many cities dependent on Colorado River water. *Georgia Droughts* – Long-term droughts (three or more years PDI < –0.99): 1756-1760; 1762-1764; 1797-1802; 1855-1857; 1896-1899; 1925-1927; 1954-1956; 1998-2002 and 2006- ? Long-term droughts (two or more years PDI < –0.99): 1756-1760, 1762-1764, 1797-1802; 1855-1857, 1896-1899, 1925-1927; 1954-1956, 1998-2002, 2006-07; 1708-1709; 1714-1715; 1839-1840; 1844-1845; 1914-1915; Return interval is now once in 25 years.

Historic Droughts of Kansas – Monthly flows recorded at 63 gauging stations were used to analyze droughts in Kansas by evaluating the cumulative departures of monthly stream flows from long-term average monthly discharges for each of the station records. As a result of the analysis, five droughts were identified: 1929-41, 1952-57, 1962-1972, 1974-82, and 1988. The 1929-41 drought was regional in scale and affected many of the midwestern and western states. The recurrence interval was greater than 25 years throughout Kansas. Although the number of stream flow records long enough to include the entire drought was insufficient, data from adjoining states confirmed the severity. Agricultural losses during the 1929-41 drought were extreme, and many farms were abandoned. The drought of 1952-57 also was regional. The drought recurrence interval was greater than 25 years statewide except in the Big Blue River Basin, where the recurrence interval was 10-25 years. Because of its severity and areal extent, the drought of 1952-57 is used as the base period for studies of reservoir yields in Kansas. The duration (number of days/months in a year) of the 1962-72 regional drought varied considerably across the State. Many of the streamflow records indicated alternating less-than-average and greater-than-average flows, whereas others indicated a steady deficit throughout the entire period. Similarly, the drought of 1974-82 appeared to be a series of relatively short-duration droughts at several gauging stations but sustained or long-term droughts at others. During the 1962-72 drought, the recurrence interval generally was greater than 25 years. However, in parts of the northwestern, northeastern, southern, and southeastern areas of the USA drought recurrence intervals were 10-25 years (Clement, 1991).

The recurrence interval of the 1974-82 drought was greater than 25 years in the north-central and southeastern parts but was between 10 and 25 years across the remaining eastern two-thirds of the State (Clement, 1991). Because of inadequate stream flow information for comparison, the severity of the 1974-82 drought could not be determined in the western one-third of the State. The severity of the 1988 drought varied across the State. The drought was most severe in the southwestern, central, and northeastern parts of the State but minimal in the northwestern and southeastern parts. At the beginning of the drought, reservoir storage was near or above average; hence, surface-water supplies were sufficient to meet demands through the end of water year 1988. Rainfall during the period generally was less than 50% of the long-term average, and quantities were insufficient to maintain soil moisture or contribute to groundwater supplies. The decreased soil moisture resulted in considerable damage to maturing grain crops, decreased the growth of forage grasses, and threatened the germination of the winter wheat crop. Water levels in the shallow aquifers declined rapidly, which resulted in the abandonment of many domestic water wells. At the end of 1988, the effects of the drought were continuing to worsen. As a result, State and local officials were considering measures to decrease water use and were requesting financial relief for the agricultural industry. The drought of 1988 continued into the 1990's, but at a reduced level. In the fall of 1989, precipitation returned to near normal, and the spring of 1990 was somewhat wet. However, by the fall of 1990 it had dried out again and continued until July of 1992. It has continued to be on the wet side since the fall of 1992, except for a dry winter of 1995-96 and the water year of 2000.

Large inter-annual fluctuations of precipitation occur routinely in *New Mexico*. However the severe drought of the 1950s clearly stands out as something unique in the twentieth century. For seven consecutive years, 1950-1956, annual precipitation was less than 12 inches. In three of those years (1951, 1953 and 1956) the annual value was less than nine inches, an amount lower than any year in the half century since then (although 2001 came close). The 1980s and 1990s were years of plentiful rainfall by comparison. Precipitation failed to exceed 12 inches only one year in those two decades. These were decades of explosive population growth in the state. It is imperative for policy makers to understand that recent climatic conditions in the 1980s and 1990s were not "normal" by any standard. The 1980s and 1990s were just as anomalously wet as the 1950s were anomalously dry. Trees in New Mexico have yielded a wealth of information on droughts and wet spells during the past millennium. The dendro-chronological record shows that the period from A.D. 622 to 1994, is from a set of trees in south-central New Mexico.

Short-term droughts hit particular spots of the United States during 1976 and 1977, which foretold the drought events that would affect many portions of the country during the 1980s. The exceptional drought of 1988 was the California Drought that lasted for five years beginning in 1987 and continuing until around 1992. And Texas has notorious histories of drought. Missouri, Arkansas, (portions of) Louisiana, Tennessee, southeast Iowa and northern Illinois were hit with severe droughts and heat during 2005. The Quad Cities themselves received only 17.88 inches of average precipitation during 2005.

Droughts can develop anywhere in the United States regardless of the patterns being El Nino, normal or La Nina. The North Atlantic Oscillation is another factor for consideration of droughts in the United States. Also, above normal dominations of high pressure system in any particular regional vicinity of the United States are known seriously for creating droughts (Fig. 9.8) and the seasonal droughts (Fig. 9.9).

The *impact of drought* in USA are observed on: (1) Grasses includes discolouring which turns grasses yellow, gold shades, tan or brown instead of green. Watering lawns is an effective way for preventing the discolouring of grass during drought. Abnormally severe drought combined with the deep plowing of the virgin top soil of the Great Plains killed the natural grasses. Such grasses normally kept the soil in place and moisture trapped, even during periods of drought and high winds. During the drought of the 1930s, with the grasses destroyed, the soil dried, turned to dust, and blew away eastwards and southwards in large dark clouds. (2) Dry skin, air stagnation and substandard health are the factors to consider regarding drought impacts on health. Still standing air becomes poisoned by putridness, strong smoke and pollutants. It's extremely common in drought years. (3) The drought caused crops to fail, leaving the plowed fields exposed to wind erosion. The fine soil of the Great Plains was easily eroded and carried east by strong continental winds. On November 11, 1933, a very strong dust storm stripped topsoil from desiccated South Dakota farmlands in just one of a series of bad dust storms that year. (4) Fireworks will not only ignite anything dry but contribute to really destructive fires which burn buildings or houses, destroying them sometimes. (5) Dry thunderstorms are notorious for starting wildfires, brush fire activity and making wildfires worse. And it's especially important in droughts, because dry timbers and dry grasses are notorious for becoming ignited by lightning.

In order to meet the overall needs assessment in the identification of conservation potential, the strategy adopted by Arizona: Creation of a statewide conservation office to implement new conservation programmes, secure a dedicated funding source for conservation office and for statewide water conservation programmes, expand the *"Reduce Your Use"* conservation messaging campaign, adoption of w*ater conservation "ABCs"* for residential and large water use sectors and encourage use of best available technologies, creation of conservation incentives (tax credits), provide technical assistance (leak detection and audit training programmes), creation of a state sponsored conservation web site, creation of voluntary benchmarks and conservation goals at local levels, continue/expand existing education programmes through working with school districts, education centres and local communities, develop partnerships to provide the funding and "buy-in" for establishing new conservation programmes, creation of a Rural Water Systems Development Fund for conservation, creation of a Water Conservation

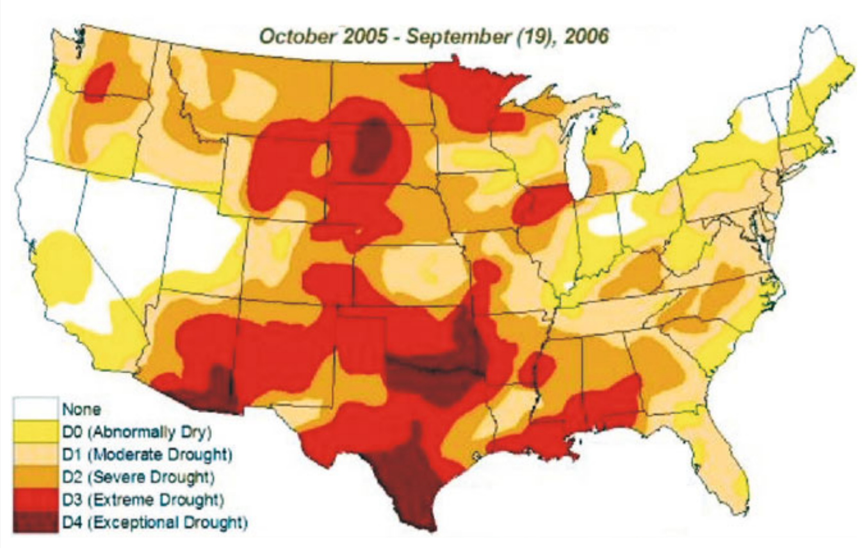
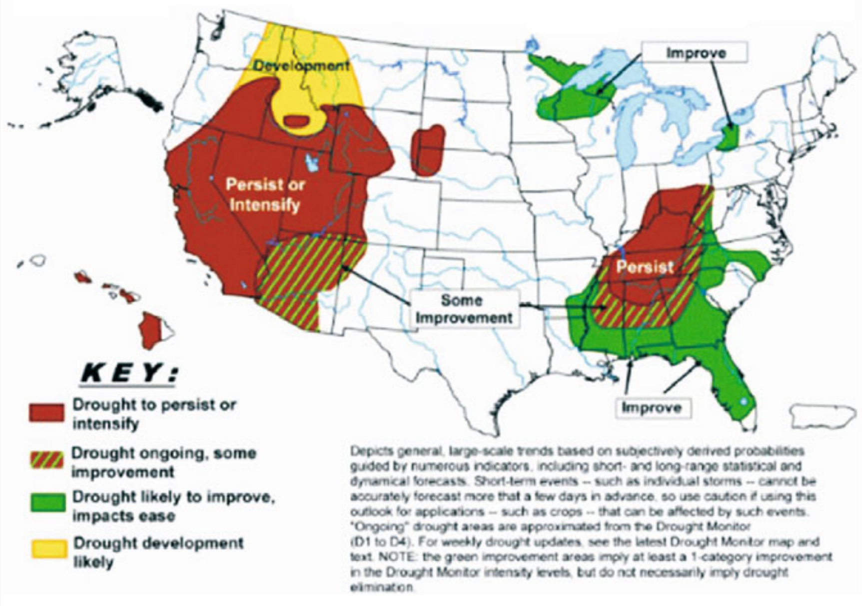


Fig. 9.8: Peak drought status in USA.
Courtesy: US Department of Agriculture



Depicts general, large-scale trends based on subjectively derived probabilities guided by numerous indicators, including short- and long-range statistical and dynamical forecasts. Short-term events -- such as individual storms -- cannot be accurately forecast more that a few days in advance, so use caution if using this outlook for applications -- such as crops -- that can be affected by such events. "Ongoing" drought areas are approximated from the Drought Monitor (D1 to D4). For weekly drought updates, see the latest Drought Monitor map and text. NOTE: the green improvement areas imply at least a 1-category improvement in the Drought Monitor intensity levels, but do not necessarily imply drought elimination.

Fig. 9.9: Seasonal drought conditions in USA.
Courtesy: US Department of Agriculture

Advisory Board and develop a water use "score card" method of programmes. Drought response actions are: Convening State Drought Task Force; intensifying monitoring and assistance; disseminating information to the public; suspending surface water appropriation permits; Governor's declaration of critical water deficiency and water use restrictions. It varies marginally from state to state.

Russia and USSR

Droughts and famines in Russia and the USSR tend to occur on a fairly regular basis, with famines occurring every 10-13 years and droughts every 5-7 years. Golubev and Dronin distinguish three types of drought according to productive areas vulnerable to droughts: Central (Volga basin, Northern Caucasus), and Central (Chernozem Region), Southern (Volga and Volga-Vyatka area, Ural, Ukraine), and Eastern (steppe and forest-steppe belts, Western and Eastern Siberia and Kazakhstan).

Pre-1900 droughts and famines – Major famines include the Great Famine of 1315–1317 which affected much of Europe including Russia, and the 1891-92 famine which killed between 375,000 and 500,000 people. Russian famine of 1601-1603 is the worst famine. It occurred in Central – 1920, 1924, 1936, 1946, 1972, 1979, 1981, 1984; Southern – 1901, 1906, 1921, 1939, 1948, 1951, 1957, 1975, 1995 and Eastern USSR - 1911, 1931, 1963, 1965, 1991 as indicated by Golubev and Dronin (1989).

The famine in the USSR which happened in 1921-1923 was due to the Southern type of drought, the most affected area being the southeastern areas of European Russia (including Volga area, or Povolzhye, especially national republics of Idel-Ural, *see* 1921-1922 Famine in Tatarstan) and Ukraine. In 1932-1933, confiscations of grain and other food by the Soviet authorities caused a famine which affected more than 40 million people, especially in the south in the Don and Kuban areas and in Ukraine, whereby various estimates from 5 to 10 million may have starved to death (the event known as Holodomor). About 200,000 Kazakh nomads fled to China, Iran, Mongolia and Afghanistan during the famine. In 1947 famine was due to a cumulative effect of consequences of collectivization, war damage, the severe drought in 1946 in over 50% of the grain-productive zone of the country and government social policy and mismanagement of grain reserves. This led to an estimated 1 to 1.5 million excess deaths as well as to secondary population losses due to reduced fertility. The 1963 drought caused panic slaughtering of livestock, but there was no risk of famine. Since that year the Soviet Union started importing feed grains for its livestock in increasing amounts.

9.4 Water Politics

There are approximately 260 different river systems worldwide, where conflicts exist crossing national boundaries. History showed that the 37 records of acute conflict over water are far less than the record of cooperation. In the last 50 years, 157 treaties were signed, and 1288 crises turned out to be co-operative opportunities. While Helsinki Rules help to interpret intrinsic water rights among countries, there are some conflicts so bitter or so related to basic survival that strife and even warfare are inevitable. In many cases water use disputes are merely an added dimension to underlying border tensions founded on other bases. The key lies in strong institutions and cooperation. The *Indus River Commission* and the *Indus Water Treaty* survived two wars between India and Pakistan despite their hostility, and was proved to be a successful mechanism in resolving conflicts by providing a framework for consultation, inspection and exchange of data. The *Mekong Committee* has also functioned since 1957 and it survived the Vietnam War. In contrast, regional instability resulted when there is an absence of institutions to co-operate regional collaboration, like Egypt's plan for a high dam on the Nile. However, there is currently no global institution in place for the management of transboundary water sources, and international co-operation had happened through ad hoc collaborations. One common feature of almost all disputes resolved is that the negotiations had a "need-based" instead of a "right-based" paradigm. Irrigable lands, population, technicalities of projects define "needs". The success of a need-based paradigm is reflected in the only water agreement ever negotiated in the Jordan River Basin; it focuses on needs and not on rights of riparians.

South and Southeast Asia, with five and 18 river basins respectively, have recorded the highest incidence of water disputes, though none went beyond an outburst of political rhetoric. There have been 237 interactions in South Asia as a result of disputes, 371 in Southeast Asia and 84 in East Asia. But four of the six most disputed basins on a worldwide basis are located either in Asia or the Middle East: Ganges-Brahmaputra-Meghna, Jordan, Tigris-Euphrates and the Mekong. In the Indian subcontinent, irrigation requirements of Bangladesh determine water allocations of The Ganges River. A need based, regional approach focuses on satisfying individuals with their need of water, ensures that minimum quantitative needs are being met. It removes the conflict that arises when countries view the treaty from a national interest point of view, move away from the zero-sum approach to a positive-sum, integrative approach that equitably allocated the water and its benefits. The Tigris-Euphrates River System is one example where differing national interests and withdrawal rights have been in conflict. The countries of Iran, Iraq and Syria each present valid claims of certain water use, but the total demands on the riverine system surpass the physical constraints of water availability. As early as 1974 Iraq massed troops on the Syrian border and threatened to destroy Syria's al-Thawra dam on the Euphrates. In 1992 Hungary and Czechoslovakia took a dispute over Danube River water diversions and dam construction to the International Court of Justice. This case represents a minority of disputes where logic and jurisprudence may be the path of dispute resolution. Other conflicts involving North and South Korea, Israel and Palestine, Egypt and Ethiopia, may prove more difficult tests of negotiation.

9.5 Drought Strategies

Water deficits are already spurring heavy grain imports in numerous smaller countries.

- *The Himalayan glaciers* that are the sources of Asia's biggest rivers – Ganges, Indus, Brahmaputra, Yangtze, Mekong, Salween and Yellow – could disappear by 2035 as temperatures rise. Approximately 2.4 billion people live in the drainage basin of the Himalayan rivers. India, China, Pakistan, Bangladesh, Nepal and Myanmar could experience floods followed by droughts in coming decades. The west coast of North America, which gets much of its water from glaciers in mountain ranges such as the Rocky Mountains and Sierra Nevada, also would be affected (UN report). *Irreversible and severe ecological damage* would take place over Murray-Darling basin, Australia, if it does not receive sufficient water by October. Perth in Western Australia could become the world's first ghost metropolis, an abandoned city with no more water to sustain its population.
- Often *technology is advanced as a panacea*, but the costs of technology presently exclude a number of countries from availing themselves of these solutions. The amount of energy needed to convert saline water to potable water is prohibitive today, explaining why only a very small fraction of the world's water supply is derived from desalination. Construction of *wastewater treatment plants* and reduction of groundwater over-drafting appear to be obvious solutions to the worldwide problem. Wastewater treatment is highly capital intensive, restricting access to this technology only in some select affordable regions; furthermore the rapid increase in population of many countries makes this a race that is difficult to win.
- Reduction in *groundwater over-drafting* is usually very unpopular politically and has major economic impacts to farmers; moreover, this strategy will necessarily reduce crop output, which is something the world can ill afford, given the population level at present. The water tables are

falling in scores of countries (including northern China, the US, and India, Pakistan, Iran, and Mexico) due to widespread over-pumping using powerful diesel and electric pumps.

- *Desalination* – As new technological innovations continue to reduce the capital cost of desalination, more countries are building desalination plants as a small element in addressing their water crises. 13,080 desalination plants located around the world, produce more than 12 billion gallons of water a day. Israel desalinizes water at a cost of 53 cents per cubic metre; Singapore desalinizes water for 49 cents per cubic metre and also treats sewage with reverse osmosis for industrial and potable use. China and India, the world's two most populous countries, are turning to desalination to provide a small part of their water needs. Pakistan announced plans to use desalination in 2007. Australia uses desalination. In 2007 Bermuda signed a contract to purchase a desalination plant. The largest desalination plant in the United States is the one at Tampa Bay, Florida, which began desalinizing 25 million gallons (95,000 m^3) of water per day in December 2007. In the United States, the cost of desalination is $3.06 for 1000 gallons. In the United States, California, Arizona, Texas, and Florida use desalination for a very small part of their water supply. A typical aircraft carrier in the U.S. military uses nuclear power to desalinize 400,000 gallons of water per day. However, given the energy intensive nature of desalination, with associated economic and environmental costs, desalination is generally considered a last resort after water conservation.
- *Drought monitoring* – Continuous observation of rainfall levels and comparisons with current usage levels can help prevent man-made drought. For instance, analysis of water usage in Yemen has revealed that their water table (underground water level) is put at grave risk by over-use to fertilize their Khat crop. Careful monitoring of moisture levels can also help predict increased risk for wildfires, using such metrics as the Keetch-Byram Drought Index or Palmer Drought Index.
- *Land use* – Carefully planned crop rotation can help to minimize erosion and allow farmers to plant less water-dependent crops in drier years. *Rainwater harvesting* – Collection and storage of rainwater from roofs or other suitable catchments. *Recycled water* – Wastewater (sewage) has been treated and purified for reuse. *Transvasement* – Building canals or redirecting rivers as massive attempts at irrigation in drought-prone areas. *Water restrictions* – Water use may be regulated (particularly outdoors). This may involve regulating the use of sprinklers, hoses or buckets on outdoor plants, the washing of motor vehicles or other outdoor hard surfaces (including roofs and paths), topping up of swimming pools, and also the fitting of water conservation devices inside the home (including shower heads, taps and dual flush toilets). *Cloud seeding* – an artificial technique to induce rainfall.

References

Allen, R.J. The Australasian Summer Monsoon, Teleconnections, and Flooding in the Lake Eyre Basin. pp. 41-42.

Bhattacharyya, K., Azizi, P.M., Shobair, S.S. and Mohsini, M.Y. (2004). Potential for Their Mitigation in Southern and Western Afghanistan. Working paper 91, Drought series 5, International Water Management Institute, Colombo.

Chilton, P.J. and Smith-Carington, A.K. (1984). Characteristics of the weathered basement aquifers in Malawi in relation to rural water supplies. Monograph.

Clement, R.W. (1991). Kansas floods and droughts. *In:* Paulson, R.W., Chase, E.B., Roberts, R.S., and Moody, D.W. (compilers). National water summary 1988-89 – Hydrologic events and floods and droughts: U.S. Geological Survey, Water Supply Paper 2375, pp. 287-294.

Cohen, S., Wheaton, E.E. and Masterton, J. (1992). Impacts of Climatic Change Scenarios in the Prairie Provinces: A Case Study from Canada. Canadian Climate Center, Downsview, ON.

Endersen, S. and Myhrstad, J.A. (1987). Multinational water schemes. Proceedings, International Water Symposium on Drought and Famine, July 1986. Olympic, London, UK.

Khouri, N. (1989). Waste water reuse implementation in selected countries of the Middle East and North Africa. *In:* Schiller, E.J. (ed.). Sustainable water resources management in arid countries: Middle East and North Africa. pp. 131-144.

Lianyou Liu (2007). Background paper on drought – An assessment of Asian and Pacific progress. UNESCO Regional Implementation Meeting for Asia and the Pacific for the Sixteenth session of the Commission on Sustainable Development (CSD-16), 26-27 November 2007, Jakarta, Indonesia.

Phillips, D. (2002). The top ten Canadian weather stories for 2001. CMOS Bull. **30** **(1)**, pp. 19-23.

Raddatz, R.L. (1998). Anthropogenic vegetation transformation and the potential for deep convection on the Canadian prairies. *Can. J. Soil Sci.*, **78**, pp. 657-666.

WFP (World Food Programme) (2003). Afghanistan countrywide food needs assessment of rural and settled populations. Kabul, Afghanistan: World Food Programme.

Wright, E.P. (1985). Water resources for humans, livestock and irrigation. *In:* Geohydrology of drought prone areas of Africa. Proceedings of a seminar-planning meeting, Lobatse, Botswana.

Further Reading

Akinremi, O.O., McGinn, S.M. and Barr, A.G. (1996). Evaluation of the Palmer Drought Index on the Canadian prairies. *J. Climate*, **9**, pp. 897-905.

Asad Sarwar Qureshi and Mujeeb Akhtar (2004). A survey of drought impacts and coping measures in Helmand and Kandahar provinces of Afghanistan. IWMI Internal Report

Ayoub, A.T. (1993). National soils policy for the protection and rational utilization of soil resources: Technical, institutional and legal aspects. Paper presented at the 1st Crop Science Conference for East and Southern Africa. June 1993, Kampala, Uganda.

Bougel, F., Champolivier, L., Lespinas, L., Merrien, A., Reau, R., Le Clech, B., and Paget (2001). Irrigation du tournesol: une methode de pilotage econome eneau, Oleoscope (cetim) 60, pp. 15-17.

Burdon, D.J. (1977). Flow of fossil groundwater. *Quarterly Journal of Engineering Geology*, **10**, pp. 97-124.

Caliandro, A. and Boari, F. (1996). Supplementary irrigation in arid and semiarid region. *Mediterrenean*, **7,** pp. 24-27.

Dennett, M.D. (1987). Variation of rainfall: The background to soil and water management in dryland regions. *Soil Use Management*, **3,** pp. 47-51.

Encyclopedia Britannica and Kammerer, J.C. (1990). Largest Rivers in the United States. US Geological Survey Fact Sheet, Open File Report 87-242.

Folland, C.K., Palmer, T.N. and Parker, D.E. (1986). Sahel rainfall and worldwide sea temperatures, 1901-85. *Nature*, **320 (6063)**, pp. 602-607. doi:10.1038/320602a0.

Forster, S.F. (1993). Transboundary river basin management in southern Africa. *In:* Van Dam, J.C. and Wessel, J. (eds.). Transboundary river basin management and sustainable development. Proceedings, Vol. 1. UNESCO/IHP, pp. 195-201.

Giannini, A., Saravanan, R. and Chang, P. (2003). Oceanic Forcing of Sahel Rainfall on Interannual to Interdecadal Time Scales. *Science*, **302 (5647)**, pp. 1027-1030.

Heidenreich, A. (1993). Pesticides in Bamako water: Is it toxic waste? *EcoNews Africa*, **2**, p. 12.

Held, I.M. et al. (2005). Simulation of Sahel drought in the 20th and 21st centuries. PNAS, **102(50)**, pp. 17891-17896. doi:10.1073/pnas.0509057102. PMID 16322101.

Herrington, R., Johnson, R. and Hunter, F. (1997). Responding to global climate change in the Canadian prairies. *In:* Canada Country Study: Climate Impacts and Adaptation, vol. III. Environment Canada, Ottawa, ON.

Katz, R.W. and Glantz, M.H. (1986). Anatomy of a rainfall index. *Mon. Wea. Rev.*, **114**, pp. 764-771.

Kogan, F.N. (1995). Droughts of the late 1980s in the United States as derived from NOAA polar-orbiting satellite data. *Bull. Am. Meteor. Soc.* **76 (5)**, pp. 655-668.

Kumar, V. and Panu, U. (1997). Predictive assessment of severity of agricultural droughts based on agro-climatic factors. *J. Am. Water Resour. Assoc.*, **33 (6)**, pp. 1255-1264.

Loss, S.P. and Siddique, K.H.M. (1994). Morphological and physiological traits associated with wheat yield increases in Mediterranean environments. *Advanced Agronomy Journal*, **52,** pp. 229-276.

Lundqvist, J. and Gleick, P.H. (2000). Sustaining our waters into the 21st century http://www.earthscape.org/r1/luj01/.

Meinke, H., Pollock, K., Hammer, G.L., Wang, E., Stone, R.C., Potgieter, A. and Howden, M. (2001). Understanding climate variability to improve agricultural decision making. Proceedings of the 10th Australian Agronomy Conference on Science & Technology: Delivering results for Agriculture? ASA, Hobart, p. 12.

Nikolai, M. Dronin and Edward G. Bellinger (2005). Climate Dependence and Food Problems in Russia, 1900-1990: The Interaction of Climate and Agricultural Policy and Their Effect on Food Problems. Central European University Press.

Otieno, F.O. and Kilani, J.S. (1991). RBC or porous pots for textile waste treatment. Proceedings, 17th WEDC Conference on Infrastructure, Environment, Water and People.

Palmer, W.C. (1965). Meteorological Drought. Research Paper No. 45, US Weather Bureau, Washington, DC.

Passioura, J.B. (1977). Grain yield, harvest index and water use of wheat. *Journal Australian Institute of Agriculture Science*, **43,** pp. 117-120.

Rijsberman, F.R. and Molden, D. (2001). Balancing water uses: Water for food and water for nature. Thematic background paper. Secretariat International Conference on Freshwater, Bonn, Germany, 18 p.

Ritchie, J.T. (1972). A model for predicting evaporation from a row crop with incomplete cover. *Water Resources Research*, **8,** pp. 1204-1213.

Rosenberg, N.J. (1978). North American Droughts. AAAS, Boulder, CO.

Rutherford, R.S.G. (1948). Fluctuations in the Sheep Population of New South Wales, 1860-1940: A Preliminary Study. *Economic Record*, **24(1)**, pp. 56-71.

UNECA (United Nations Economic Commission for Africa) (1989). Economic aspects of drinking water supply and sanitation in Africa with particular reference to rural areas. ECA/NRD/WRU/4/89, TPUB/9901.

UNSO (United Nations Sudano-Sahelian Organization) (1991). Assessment of desertification and drought in the Sudano-Sahelian region 1985-1991.

Wheaton, E.E., Arthur, L.M., Chorney, B., Shewchuk, C., Thorpe, J. and Whitting, J., Whittrock, K. (1992). The prairie drought of 1988. *Climatol. Bull.*, **26**, pp. 188-205.

Wilhite, D.A., Rosenberg, N.J. and Glantz, M.H. (1986). Improving federal response to drought. *J. Climate Appl. Meteor*. **25**, pp. 332-342.

Zhang, Rong and Delworth, Thomas L. (2006). Impact of Atlantic multidecadal oscillations on India/Sahel rainfall and Atlantic hurricanes. *Geophysical Research Letters*, **33**: L17712. doi:10.1029/2006GL026267.

Zima, V.F. (1999). The Famine of 1946-1947 in the USSR: Its Origins and Consequences. Ceredigion, UK: Mellen Press.

Index