Chapter 2
Aridity and Drought

2.1 Definition of Aridity

Aridity is a term that most people conceptually understand, and it evokes images of dry, desert lands with sparse natural surface-water bodies and rainfall, and commonly only scant vegetation, which is adapted to a paucity of water. Aridity has a wide variety of landscape manifestations (Fig. 2.1) including barren rock hills and plains, sand dune fields, and vegetation dominated by cacti and other xerophytic plants. Despite their usual parched appearance, deserts can become remarkably verdant when rain does fall (Fig. 2.1d). The primary focus of this book is largely on arid and semiarid lands with warm climates in which water scarcity is more severe because of greater populations and associated water use. However, aridity also occurs in regions with cold climates in which precipitation falls mainly as snow. Much of Antarctica and the Arctic slope of Alaska are considered to be polar deserts because they receive little net precipitation each year (Smiley and Zumberge 1971).

Non-technical dictionaries typically define the word arid with respect to climate in terms such as barren, parched, dry or without moisture, or as having insufficient water, rainfall or precipitation to support vegetation or agriculture. However, it is difficult to define "arid" precisely and delineate the boundary between different degrees or levels of aridity or its opposite, humidity. For example, what is the threshold for an area to be considered arid instead of semiarid and what are the specific landscape and water resources manifestations of an arid versus semiarid climate?

Numerous climatic and biological classifications have been proposed for arid lands (McGinnies 1988). Aridity, as defined by the shortage of moisture, is essentially a climatic phenomenon that is based on average climatic conditions over a region (Agnew and Anderson 1992). A fundamental distinction exists between aridity, which is a long-term climatic phenomenon and droughts, which are a temporary phenomenon (water deficit). Thornthwaite (1948) recognized that

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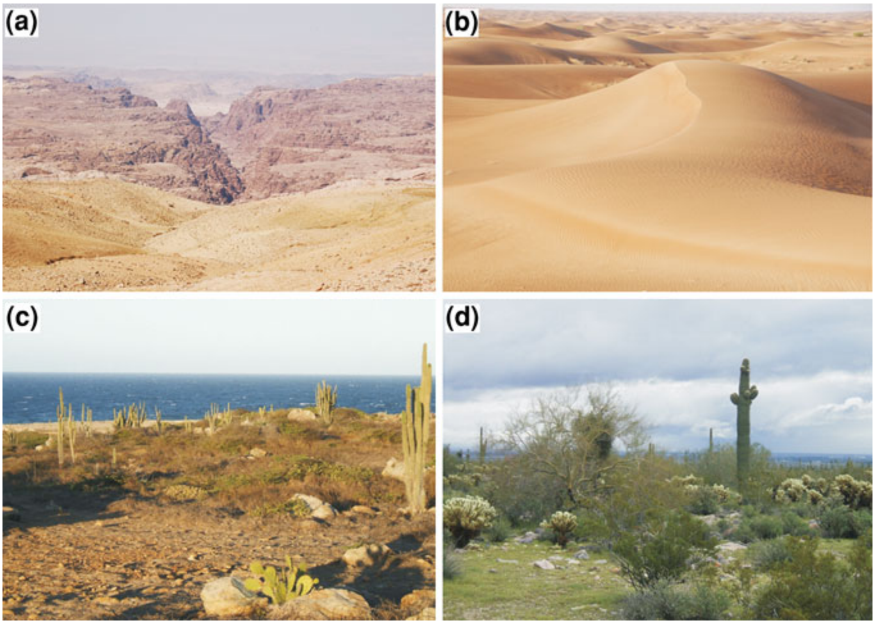

Fig. 2.1 Desert landscapes. **a** Rocky desert in southwestern Jordan (photo by Weixing Guo). **b** Sand dune field in Abu Dhabi, United Arab Emirates. **c** East coast of Aruba, near Noord. **d** Sonoran Desert near Phoenix, Arizona, USA, after rains

whether a climate is moist or dry is dependent upon both the amount of precipitation and whether or not the precipitation is greater or less than the water needed to offset evaporation and plant transpiration, which are collectively termed evapotranspiration (ET). In other words, aridity is a function of both precipitation and the potential evapotranspiration rate (ET_p). An additional factor effecting aridity is temperature and the annual timing of precipitation. Rainfall during cold seasons is more effective in areas with a sufficiently high temperature for plant growth, because less water is lost to direct evapotranspiration during cold periods than in the hot season (Walton 1969).

Potential evapotranspiration is the amount of transfer of water to the atmosphere that would be possible under ideal conditions of soil moisture and vegetation (Thornthwaite 1948). Penman (1948, 1956) more precisely defined potential evapotranspiration as "the amount of water transpired in a given time by a short green crop, completely shading the ground, of *uniform* height and with adequate water status in the soil profile". A critical issue for arid region water resources is the difference between ET_p and the actual rate of evapotranspiration (ET_a). Potential evaporation rates in some arid regions (e.g., Arabian Peninsula) may exceed 4 m (13.1 ft) per year. However, the actual rate of evapotranspiration in land areas depends upon the amount of moisture available. A characteristic feature of warm arid land areas is that ET_a rates are actually very low because of the paucity of water that is available for transfer to the atmosphere. On the contrary, the ET_a rates of surface water bodies in arid lands are very high, approaching ET_p values. The high ET_a rates results in a loss of water and the concentration of salts.

2.2 Aridity Indices

Numerous numerical indices have been proposed to quantify the degree of dryness of a climate at a given location, and thus define climatic zones. Aridity indices were reviewed by Walton (1969) and Stadler (2005). There is a lack of agreement over the approaches used to delineate the exact boundaries between lands having different levels of aridity, although there is an agreement over the general location of arid regions (Agnew and Anderson 1992). Aridity indices inherently include an element of circularity in that they are calibrated against known aridity patterns. For example, the Atacama Desert of northern Chile is widely recognized to be the driest desert in the world. Hence, the numerical thresholds for the extremely arid or hyperaridity category for aridity indices are based on the values of the indices for the Atacama Desert and similar areas.

Several commonly used aridity indices are discussed herein to illustrate basic concepts. From a practical water management perspective, aridity indices do not have much relevance. It is typically self-evident that an arid region under investigation is indeed arid. Nor is there a strong reason to prefer one index to another with respect to water management. Aridity indices have greater value for the tracking the effects of climate change on local water resources, if sufficiently accurate data are available for mapping local changes in the values of the indices over time.

The simplest aridity index is based solely on precipitation. A commonly used rainfall-based definition is that an arid region receives less than 10-in or 250 mm of precipitation per year. This criterion for aridity was used by the Intergovernmental Panel on Climate Change (IPCC 2007). Semiarid regions are commonly defined by annual rainfalls between 10 and 20-in (250 and 500 mm).

The UNESCO (1979) aridity index (AI) is based on the ratio of annual precipitation (P) and potential evapotranspiration rates as follows:

$$AI = \frac{P}{ET_p} \tag{2.1}$$

where, ET_p is calculated using the Penman (1948) formula. The UNESCO system is attractive in that it is conceptually and operationally simple and is based solely on the two main parameters that define aridity. Warm arid regions have low P and high ET_p rates and thus very low AI values. UNESCO (1979) proposed a classification of climate zones based on AI index, in which arid regions are defined by an index of less than 0.20 (Table 2.1). Alternative versions of the classification use an AI value for 0.05 for the boundary between hyperarid and arid regions.

Table 2.1 UNESCO (1979) Aridity classification

Classification	Aridity index
Hyperarid	$AI < 0.03$
Arid	$0.03 < AI < 0.20$
Semi-arid	$0.20 < AI < 0.50$
Dry subhumid	$0.50 < AI < 0.65$

Data on local ET_p rates may not be available, which constrains the use of the UNESCO index. The De Martonne (1926) aridity index (A_m) instead uses temperature as a proxy for ET_p as follows:

$$A_m = \frac{P}{T + 10} \quad (2.2)$$

where, P (cm) is the annual precipitation and T (°C) the annual mean temperature. The equation is appropriate for temperatures greater than –9.9°C. The De Martonne aridity index decreases (approaches zero) with increasing aridity.

The Thornthwaite (1948) classification scheme, and variations thereof, is also commonly used to map the distribution of non-polar dry lands. Meigs (1953) prepared a map of the distribution of non-polar arid regions for UNESCO based on the Thornthwaite classification, which still widely cited (Fig. 2.2). Thornthwaite (1948) defined indices of humidity (I_h) and aridity (I_a) as follows:

$$I_h = \frac{100\,s}{n} \quad (2.3)$$

$$I_a = \frac{100\,d}{n} \quad (2.4)$$

where,

s = surplus water, which is defined as the sum of the monthly difference between precipitation (P) and ET_p for those months when P exceeds ET_P (cm)

d = water deficiency, which is defined as the sum of the monthly difference between ET_P and precipitation (P) and for those months when ET_p exceeds P (cm)

n = water need, which is the sum of monthly values of potential evapotranspiration for the surplus or deficiency months (cm).

Thornthwaite (1948) then defined the moisture index (I_m) as follows:

$$I_m = I_h - 0.6 I_a \quad or \quad \frac{100\,s - 60\,d}{n} \quad (2.5)$$

Thornthwaite (1948) considered the semiarid climate type to have a moisture index between –20 and –40 and the arid climate type to have a moisture index between –40 and –60.

It must be emphasized that the exact numerical cut-offs between the different climate classes are arbitrary lines drawn in a climatic continuum and that they do not represent a fundamental climatic change. For example, the climatic different

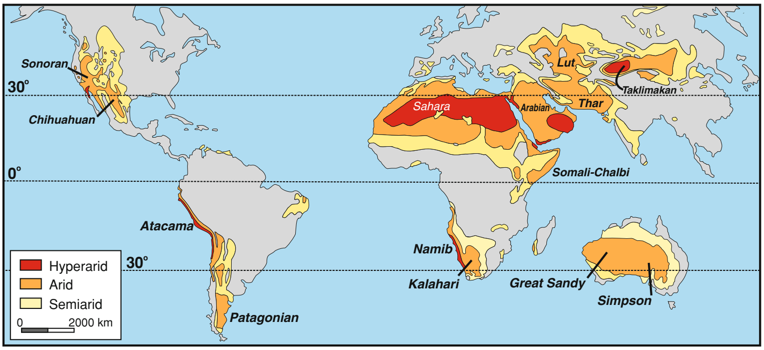

Fig. 2.2 Map of distribution of non-polar arid lands (after Meigs 1953). *Source* http://pubs.usgs.gov/gip/deserts/what/world.html

between areas with UNESCO aridity indices of 0.19 and 0.21 would not be significant yet they would be assigned to different classifications (arid and semiarid, respectively).

2.3 Causes of Aridity

Rainfall occurs when moist air is cooled through either the process of ascent, mixing, radiation cooling, or contact cooling. The processes leading to aridity tend to prevent such cooling through maintaining air stability, creating temperature inversions, or through warming of the atmosphere. Descending air tends to get warmer, which decreases its relative humidity and increases its "dryness". Most arid lands lie in the tropics and therefore, receive substantial inputs of solar radiation energy, which can be expended on heating the environment, wind generation, or be utilized for evaporation (Walton 1969; Agnew and Anderson 1992).

There are four main causes of regional aridity (Thompson 1975; Agnew and Anderson 1992):

(1) *High pressure*: Air heated at the equator rises, moves towards the poles, and then descends in the subtropics at around 20 to 30° north and south latitude (Fig. 2.3a). Compression and warming of the descending air mass leads to dry and stable atmospheric conditions (e.g., Sahara Desert). This atmospheric circulation pattern is referred to as the "Hadley cell."

(2) *Continental winds*: Winds blowing across continental interiors have a reduced opportunity to absorb moisture and are fairly stable with low humidity (e.g., SW Asia, Middle East). It is not the absolute distance from oceans that is important, but rather the distance from the ocean along the moist airstream flow paths (Walton 1969).

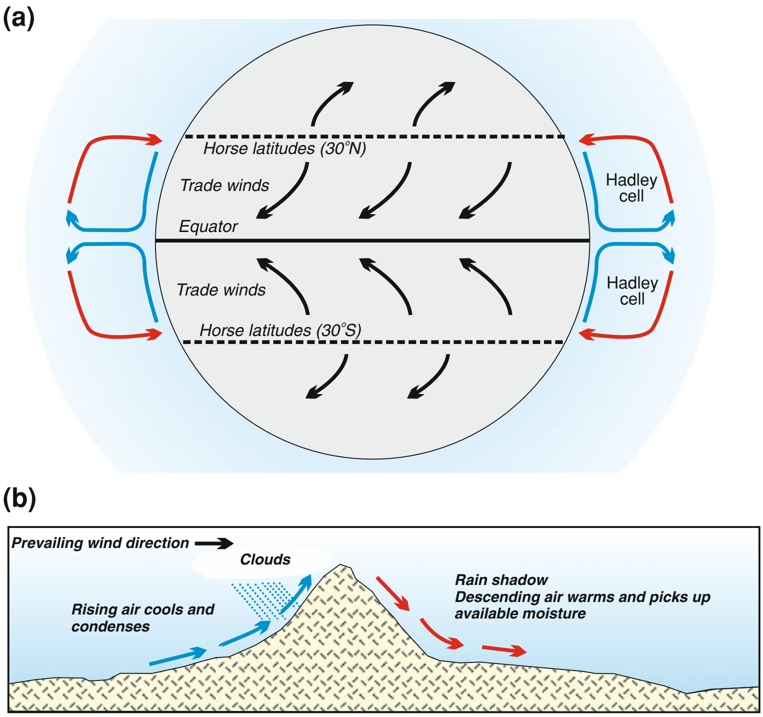

Fig. 2.3 Cause of aridity. **a** Hadley cell circulation. Air is warmed and rises to the top of troposphere near the equator. The cooled air descends in the subtropics, creating a zone of dry and stable high-pressure conditions. **b** Rain shadow effect. Rising air at the windward slope of mountain ranges cools and loses moisture. Descending air on the leeward sides of mountains warms during descent, decreasing its relative humidity

(3) *Rain shadow effect*: The cooling of air forced aloft by mountain ranges causes precipitation and a loss of moisture. The descending air on the leeward side of the ranges is warmer at a given altitude compared to the windward side because of the greater adiabatic lapse rates (rate of temperature change with elevation) of dry air compared to moist or saturated air. The windward sides of mountain ranges may have high rates of precipitation, while the leeward sides (a relatively short geographic distance away) may have semiarid or arid conditions (e.g., northern Rocky Mountains USA) (Fig. 2.3b).

(4) *Cold ocean currents*: Cold ocean currents near land can cool the lower atmospheric, but warmer air aloft creates a temperature inversion that prevents the ascent of air and thus precipitation. As the cool air moves inland it is warmed and as a result its humidity decreases (e.g., coastal Peru, Oman, and Namibia).

Aridity is mainly the result of large-scale, persistent, atmospheric and oceanic circulations patterns or regional geography and topography. The cause of aridity is not generally germane to local groundwater management. Aridity, and associated water scarcity, is a long-term, hydrologic and climatic condition with which local populations must adapt irrespective of its cause. However, the cause of aridity is significant within the context of global climate change, which may impact global atmospheric and oceanic circulation patterns (Chap. 39). For example, global warming may result in an expansion or shift of the Hadley cells, which could increase the extent and change the positions of the subtropical dry zones.

2.4 Droughts

2.4.1 Definition of Droughts

Drought is a concept that is generally understood on a basic level, but is difficult to quantify. Palmer (1965, p. 2) defined a drought as a meteorological phenomenon that is characterized by "prolonged and abnormal moisture deficiency", and more specifically (p. 3) as

> An interval of time, generally on the order of months or years in duration, during which the actual moisture supply at a given place rather consistently falls short of climatically expected or climatically appropriate moisture supply.

A drought can alternatively be broadly defined as a temporary, recurring reduction in the precipitation in an area. Key words are 'temporary', 'reduction' and 'recurring'. The term 'reduction' implies that water levels are less than what are considered normal. The term 'recurring' signifies that droughts are a normal part of the climatic cycle. Droughts are thus not 'abnormal' events, but are rather low-end extremes in the normal variation in the overall water supply.

Aridity and drought are not synonymous. Aridity is a measure of long-term average climatic conditions. Both humid and arid regions experience droughts. However, the inter-year variation in precipitation is greater in arid regions and there is a greater probability of below average precipitation in any particular year (Smakhtim and Schipper 2008). Arid regions are thus more prone to droughts and may experience more severe impacts from droughts.

The definition of drought has real world consequences. The misidentification of recurring temporary dry spells as droughts, which implies an extreme abnormal situation, can result in societies becoming maladapted and increasingly vulnerable because of unnecessary asset depletion or inappropriate mitigation measures (Smakhtin and Schipper 2008). As noted by Smatkhtin and Schipper (2008, p. 137)

> If people, agriculture and industries are adversely affected by normal climatic fluctuations, the problem is not really related to drought. Instead, this points to a high vulnerability of the population and/or economic sectors to already existing climatic variability.

Frequent droughts at a specific location suggest that a problem with the quantitative definition of a drought is likely (Smakhtin and Schipper 2008).

Frequent droughts in a region could be a temporary statistical anomaly (i.e., chance occurrence of multiple rare events within a short time period), an unrecognized cycle rooted in global climate variation (e.g., a dry phase of a multi-decadal climatic cycle), a manifestation of a longer-term change in local climate to more arid conditions, or perhaps reflect a poor characterization of local climate conditions. Insufficient monitoring data may be available to properly statistically characterize the true natural variations in rainfall. Apparent frequent droughts may occur if the historic climatic record for a station coincides with a wetter than normal period, and current rainfall patterns are close to the drier norm.

Persistence of drought conditions may indicate the onset of drier conditions due to climate change, requiring the reevaluation of what is normal (Agnew and Anderson 1992), at least on a water management time scale. Cyclicity in climatic conditions occurs on multiple-time scales, ranging upwards to the 10,000's of years for the Earth orbital-driven (Milankovitch) glacial cycles (Hays et al. 1976; Muller and MacDonald 1997; Roe 2006). Shorter-term climatic variations, such as the Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO), appear to have a major influence on multidecadal drought frequency in some areas (e.g., United States; McCabe et al. 2004).

The definition of droughts needs to consider (Dracup et al. 1980):

- nature of the water deficit that is being considered (e.g., precipitation, stream flow, soil moisture)
- averaging period (e.g., days, months, years)
- selection of the truncation level (cut off) to separate droughts from the remainder of the time and
- regional aspects.

A drought is a period of less than normal water supply, which needs to be considered within the context of the temporal pattern of local uses of water and how they can be altered or redistributed to temporarily meet the demands. The nature of the water deficit that is considered should be that which has the greatest impact on man's activities in the affected area (Dracup et al. 1980). For example, if an area is dependent on hydroelectric power, streamflow may be the water-supply parameter of primary interest. On the contrary, soil moisture will be a critical parameter in areas that practice dryland agriculture. However, water-supply shortages ultimately stem from meteorological conditions.

Climatic data are typical evaluated using smoothing techniques to reduce the affects of random fluctuations and to evaluate and clarify long-term trends in a time-series of data (e.g., daily rainfall readings). A common technique is moving average smoothing, which is either the sum or average value over a specific averaging period. For example, the trailing moving six-month total rainfall for a given time period is the sum of daily rainfall values over the 6 month period immediately preceding the established starting date. Increasing the averaging period tends to reduce the variance of the data and smooth out fluctuations.

The selection of the averaging period for a particular water-supply investigation is dependent almost entirely on the purpose of the study (Dracup et al. 1980) and the sensitivity of the system to water deficits of varying durations and magnitudes. Shorter averaging periods will result in a greater number of calculated drought (extreme) events. Shorter averaging periods will also result in increased serial correlation in which conditions during a given time period are affected by previous conditions (i.e., time periods are not independent events). For example, single months in which the total monthly rainfall is 20% below normal (i.e., long-term mean) will occur more frequently than months in which the trailing 12 month total rainfall total was 20 % below normal.

The deficit period used to define a drought needs to consider the sensitivity of local populations to water deficits of different durations. Using the above example, a rainfall deficiency over a single month may not have significant adverse impacts and thus would not qualify as a drought. However, a 20 % deficiency in rainfall over a 12-month period may over-tax available water storage and supply infrastructure and, therefore, have serious societal impacts.

A critical issue for identifying and quantifying droughts is the local historic rainfall distribution (i.e., what is “normal”?). The size of the historical water supply data is important in determining the type and accuracy of the analysis that may be performed. The sample size must be large enough to guarantee that sample statistics are reasonable approximations of the corresponding population parameters (Dracup et al. 1980). The frequency of rare statistical events (e.g., 100-year drought) inherently has large uncertainties if there are limited historical data.

For a region to receive its long-term average annual precipitation in a year is a rare event. Most years will be either wetter or drier than the mean or median. The key issue concerning the definition of drought is when does a deficiency in precipitation (or stream flow or soil moisture) reach a threshold (truncation level) so that a region is experiencing a true ‘drought’ as opposed to just a drier than normal year (i.e., temporary dry spell). In addition to intensity (i.e., magnitude of the precipitation deficiency), droughts must also be defined in terms of duration. The severity of a drought is the product of the magnitude of the water supply deficit and its duration. It is generally understood that a drought is a prolonged water shortage relative to the climatic norm at a location, but the necessary length of time for a dry period to become a drought is not universally defined and may ultimately depend upon local circumstances and impacts.

Droughts have a relatively strong spatial component in arid regions because of the spatial variability of rainfall (Şen 2008). Nearby areas, thus, may have different exposures to a drought depending upon where infrequent rainfalls occurred. Local areas may also be impacted by droughts caused by deficits in rainfall elsewhere in a watershed. Downstream communities dependent on river flows for water supply, for example, can be impacted by rainfall deficits in the upper basin of rivers.

Although droughts are ultimately a meteorological phenomenon, from a water management perspective, they are usually defined in terms of their impacts, particularly on human activities. A myriad of definitions of droughts have been proposed in the technical literature, which involves consideration of the magnitude of the reduction in water supply, the normal variation in water supply, the impacts of the reductions, and ideally a quantitative criterion (or criteria) for when the reduction in water supply reaches the drought threshold. Smakhtin and Schipper (2008) cautioned that because of the difference in drought manifestations, there cannot and probably should not be a universal quantitative definition of a drought.

Several different general types of droughts have been recognized, which were proposed by Subrahmanyam (1967), Matthai (1979) and Wilhite and Glantz (1985), and subsequently discussed in numerous papers and reports (e.g., Agnew and Anderson 1992; Williams-Sether et al. 1994; National Drought Mitigation Center 2006). The main drought types are:

- meteorological drought, which is defined only in terms of precipitation deficiencies, in absolute amounts, for a given period
- climatological drought, which is defined in terms of precipitation deficiencies, in percentages of normal values
- atmospheric drought, which is defined not only in terms of precipitation deficiencies but also in terms of temperature, humidity, or wind speed
- agricultural drought, which is defined principally in terms of soil moisture and plant behavior
- hydrologic drought, which is defined in terms of reduction of streamflow, reduction in lake or reservoir storage, and lowering of ground-water levels
- socioeconomic drought, which occurs when the demand for an economic good exceeds supply as a result of a weather-related shortfall in water supply
- water-management drought, which characterize water-supply shortages caused by the failure of water-management practices or facilities, such as an integrated water-supply system and surface or subsurface storage, to bridge normal or abnormal dry periods and equalize the water supply throughout the year (Matthai 1979).

Regulatory droughts may be added to this list, whereby water may be physically available, but its use is precluded by regulatory policy. For example, groundwater or surface water abstractions may be limited at times in order to maintain environmental flows in streams or wetland water levels. However, every type of drought is always ultimately a meteorological drought (Smakhtin and Schipper 2008). An important distinction is between drought and drought impacts. As can be observed in the listed definitions, the term ‘drought’ is frequently used to refer to the adverse impacts of the deficiency in rainfall, rather than to the deficiency of rainfall as a meteorological event (Smakhtin and Schipper 2008). The local societal impacts of droughts (i.e., water deficiencies), depend upon the adaptive capacity of the affected societies. Societies vary greatly in their capacity to cope with temporary water scarcity.

2.4.2 Impacts of Drought

In economic terms, droughts are the most costly natural disaster to strike the United States (Cook et al. 2007) and many other countries. The primary impact of droughts is on food production, as agriculture is by far the largest water user.

Droughts may also have severe environmental, economic, and social impacts. The environmental and socioeconomic impacts of droughts are controlled to a large degree by the duration of droughts, rather than their severity, because recovery from the cumulative damage of consecutive drought years is more difficult (Cook et al. 2007). The impacts of drought also depend upon human and ecosystem demand for water, available water-resources management capabilities and practices, as well as the meteorological and hydrological characteristics of the drought (Loucks and Gladwell 1999).

Vulnerability to droughts depends in part on the gap between average water use and the safe yield of a system (Frederick and Schwarz 2000), and the adaptive capacity of the water system and society as a whole. The greatest vulnerability occurs when water supplies are already stretched to meet demands during normal hydrologic conditions. Many regions simply do not have the food, water, and economic resources to overcome multiple-year droughts, particularly in water-stressed regions where resources even during normal years may be barely adequate (or inadequate) to meet local needs (e.g., Ethiopia and some other African countries). Vulnerability to droughts is also related to whether the primary water source is groundwater or surface water. Areas dependent on surface water tend to be more vulnerable to droughts because the impacts of reduced precipitation are felt quicker. On the contrary, urban areas that are supplied water primarily by desalination (e.g., many major coastal cities the Middle East), have a very low vulnerability to droughts. The impact of droughts also depends upon the degree of societal development, its per capita GDP, and the density of the rural population (Le Houérou 1996). Droughts have also had severe impacts on some ancient cultures, and may have contributed to, or were the primary cause of the cultural collapse (Chap. 21).

The human and economic impacts of droughts have a strong spatial component. To local communities facing the brunt of drought conditions, the impacts can be catastrophic, including loss of income, malnutrition, starvation, and migration. However, the impacts of drought decrease at greater geographic and political scales, and some regions or economic groups may actually benefit from droughts. For example, unaffected farmers may benefit from higher prices for their crops (Frederick and Schwarz 2000).

Planning for and adapting to drought conditions are complicated by droughts usually lacking a clearly defined beginning and often a clearly defined end (Loucks and Gladwell 1999). Droughts have a slow initiation and they are usually only recognized when the drought is already well established. The slow initiation and undefined end of a drought makes it very difficult to take defensive actions (Pereira et al. 2002). A period of drier than normal conditions could be either a dry spell that is about to end, the onset of longer-term drought that will have severe impacts on water users, the beginning of an unrecognized natural climatic fluctuation, or the beginning of a climatic change to increasing aridity. Megadroughts lasting for decades or centuries have been documented in the paleoclimatic record (Sect. 21.8). Similarly, a period of rainfall during a drought may represent either the breaking of the drought condition or just a temporary, short-term event in a continuing drought. An important challenge is the development of prediction and early warning skills to provide lead time to implement policies and measures to mitigate the effects of droughts (Pereira et al. 2002).

2.4.3 Drought Indices

A variety of drought indices have been developed to quantify whether or not a region is experiencing a drought and to categorize the seriousness of the drought. Water resources need to be managed on a continuous basis, so whether or not water shortages cross a specified numerical threshold does not have great operational significance. Drought indices are useful for mapping regional water supply trends, both temporal and spatial. Drought indices are also used to define disaster conditions that qualify for government assistance and where and when emergency water restrictions may be required. Drought indices were reviewed by Hayes (2007).

2.4.3.1 Percentage of Normal Precipitation

The percentage of normal precipitation is the actual precipitation divided by the local normal precipitation (e.g., 30-year mean) and multiplied by 100%. The percentage of normal precipitation is calculated for a variety of time scales. The limitation of percentage of normal precipitation is that rainfall is not normally distributed and in arid regions the mean rainfall may be substantially greater than the median rainfall because data are skewed by infrequent major wet events. The advantage of the method is its simplicity and understandability.

2.4.3.2 Palmer Drought Severity Index

The Palmer Drought Severity Index (Palmer 1965) is a soil moisture balance method in which the primary inputs are precipitation, evapotranspiration, and the soil available water capacity (AWC). Evapotranspiration is calculated using the Thornthwaite (1948) formula. The PDSI is widely used in the United States and was derived so that a given index value has the same climatological meaning regardless of location. The limitations of the method were described by Alley (1984), which included its complexity. Application of the PDSI is difficult in many parts of the world due to the absence of the data required for its application (Şen 2008).

2.4.3.3 Standardized Precipitation Index

Standardized precipitation is defined as the difference from the mean for a specified time period divided by the standard deviation, where the mean and standard deviation are determined from past records (McKee et al. 1993). SPI values are calculated for various time scales. The long-term precipitation data are fitted to a probability distribution, which are transformed to a normal distribution so the mean SPI for the location and time period is zero. Drought occurs when the SPI continuously reaches an intensity of –1.0 or less and ends when the SPI becomes positive. The SPI is the most widely used drought index and has the advantage that it is based only on precipitation and, thus, has a lesser data requirement than the PDSI.

2.5 Deserts and Desertification

The term "desert" is usually loosely defined as an area receiving little rainfall. Deserts are often described in terms of the manifestations of their water scarcity, such as the absence of permanent surface water bodies (with the exception of rivers originating outside of the desert), an often sparse flora that is adapted to dry conditions (xerophytes), and a sandy or rocky land cover. The term "desert" is widely used synonymously with arid and hyperarid regions. The US Geological Survey defines desert as a region receiving less than 10 inches (25 cm) of rainfall per year.

Desertification is the defined by the United Nations Convention to Combat Desertification (UNCCD) to mean land degradation in arid, semiarid, and dry sub-humid areas resulting from various factors including climatic variations and human activities. Land degradation is in turn defined as the reduction or loss of the biological or economic productivity of land (Millennium Ecosystem Assessment 2005). The UNCCD definition is, in some respects, unsatisfactory in that it includes both natural and anthropogenic causes, which is an important distinction. Mitigation options are available for anthropogenic desertification, which includes discontinuing or modifying the activities responsible for land degradation, which may not be a practical alternative to cope with natural desertification. Natural desertification is a normal process resulting from climatic change. For example, the Sahara Desert has alternated between wet (savanna) and desert conditions during Pleistocene and Holocene time in response to natural global climate changes (Haynes 2001; White and Mattingly 2006).

Desertification is recognized as being one of the greatest threats to global food security. It is common in dry lands, but is by no means restricted to these areas (Le Houérou 1996). The term "desertification" is not applied to natural deserts. Desertification has been occurring for more than a thousand years, but it was not until the 20th century that it was considered to be a serious problem because the option had earlier been available to move on to new lands (Dregne 1986).

Desertification is a process, and there is no firm agreement as to what the threshold is for land to be considered "desertified". It is recognized that there is a continuum in the degree of desertification. Dregne and Nan-Ting (1992) categorize degrees of desertification, ranging from slight to very severe, based on the declines in agricultural productivity. Very severely desertified land was considered by

Dregne and Nan-Ting (1992) to have decreases in productivity of 50 % or more. The Millennium Ecosystem Assessment (2005) suggested a broader, but more difficult to measure, criterion of a decrease to the capacity of ecosystems to supply services.

2.5.1 Great Plains Dust Bowl of the 1930s

Perhaps the best known example of desertification is the Dust Bowl, which impacted the Great Plains of the Western United States in the 1930s. The Dust Bowl was one of greatest environmental catastrophes ever. It affected approximately 400,000 km^2 (100,000,000 acres) of land that was centered in parts of the states of Texas, Oklahoma, New Mexico, Colorado, and Kansas (Worster 1979). The name Dust Bowl refers to the enormous dust storms, which in some instances reached the eastern coast of the United States. Drought conditions and dust storms destroyed crops, covered lands with sand dunes, suffocated animals, caused respiratory illnesses in humans, damaged and covered structures, carried away huge quantities of valuable top soil, and resulted in enormous economic losses (Fig. 2.4). Hundreds of thousands of people were forced to migrate from the region. Numerous technical books and articles have been written on the causes and agricultural, economic, and social impacts of the Dust Bowl. The Dust Bowl also had profound cultural impacts, which are reflected in novels, movies, and music.

Droughts are a frequent occurrence in the Great Plains, but dust bowl conditions are not. The ultimate cause of the dust bowl was environmentally maladapted agricultural practices (Worster 1979). The native grasses (sod) in the Great Plains protect the soil from erosion and also minimized surface water runoff. In order to maximize wheat production, the land was stripped of its native vegetation to such an extent that there was no protection against the wind. The farmers as a matter of pride were at that time referred to as "sodbusters." Agricultural operations expanded greatly in the 1920s due to a combination of wetter than average conditions and mechanizations, which allowed for larger farms to be developed.

Worster (1979) discussed the deeper socio-economic causes of the dust bowl. First was an economic drive for greater prosperity, which drove farmers to plant more and more wheat, and thus "bust" more of the native sod. An additional important factor was a belief that farmers could overcome any deficiencies in the land and climate. For example, there was at that time what would be considered now an absurd belief that the "rains would follow the plow." Agriculture was viewed as being autonomous with respect to the environment.

The Dust Bowl revealed the need for improved agricultural practices in the Great Plains, such as terracing and planting trees to form shelter belts. As the rains returned and grain prices increased in the 1940s, there was a renewal in the maladapted agricultural practices that caused the Dust Bowl (Worster 1979).

Fig. 2.4 Images of the extreme land degradation during the Dust Bowl of American Great Plains in the 1930s. Formerly productive farm lands were devastated. (Cimarron County, Oklahoma, April, 1936, Arthur Rothstein, photographer. *Source* U.S. Library of Congress

Lessons of the Dust Bowl were quickly forgotten or ignored. The area impacted by the Dust Bowl has recovered and the Great Plains are called the "bread basket of world" for its winter wheat harvest. However, current agriculture is now largely supported by unsustainable groundwater pumping.

2.5.2 Causes and Management of Desertification

Desertification in drylands is ultimately the result of long-term failures to balance demand for and supply of ecosystem services (Millennium Ecosystem Assessment 2005). The direct causes of desertification stem largely from drastic reduction or destruction of the perennial plant cover and a simplification of the vegetation structure, which results in declines in the structure of soils. Soils become subject to erosion by wind and water, salinization by evaporation, trampling by animals, and water logging in topographic depressions (Le Houérou 1996). Anthropogenic factors that can result in desertification include over-exploitation, over-grazing, bad irrigation practices, illegal and excessive logging, bush and forest fires, and deforestation due to population increases (Le Houérou 1996; Holtz 2008). Desertification and land degradation are not sudden, spectacular events, but rather gradual processes usually resulting from continued poor land management practices.

Land areas differ in their susceptibility to degradation depending upon their characteristics and climate (Eswaran et al. 2001). However, it has been observed that lands that are kept free from human and livestock interference (e.g., uninhabited areas, parks, and preserves) usually do not undergo any kind of degradation or desertification even under drought conditions (Dregne 1986; Le Houérou 1996). Native plant and animal communities are typically adapted to survive droughts and recover once drought conditions ease. Adverse climatic conditions may not be the primary cause of desertification, but may trigger or accelerate the process (Le Houérou 1996). The "deadly combination" is land abuse during good periods and its continuation during periods of deficient rainfall (Dregne 1986).

Desertification is having profound impacts on many societies as it results in reduced land productivity, and thus the food supply, causing or aggravating famine, malnutrition, poverty, and migratory movements (Holtz 2008). It is a long-lasting process that can have irreversible consequences for the production potential of the land and the local environment. Many areas that are particularly vulnerable to desertification, such as semiarid to weakly arid regions of Africa and Asia, cannot afford losses in agricultural productivity (Eswaran et al. 2001). As lands can no longer sustain their current populations, people are forced to migrate to other lands (increasing their population) or to urban slums (Le Houérou 1996). Increases in population due to the influx of migrants can, in turn, exacerbate local desertification. Over 1 billion people in over 100 countries are directly affected by desertification or are at risk (Holtz 2008) and an estimated 250 million people in developing countries have already been affected by severe land degradation (Reynolds et al. 2007).

Desertified land can be restored. Indeed, when money is of no concern, virtually any land can be restored to something approximating its original productivity (Dregne and Nan-Ting 1992). Restoration of desertified lands is cost-effective if the income generated as a result of restoration exceeds the costs of the restoration. Economic analyses of land restoration are complicated, particularly in developing countries, because of the difficulty in quantifying local crop values and labor costs for what is considered to be subsistence farming. Nevertheless, Dregne and Nan-Ting (1992) calculated that 1,860 billon hectares (7.2 million mi^2) of desertified land could be repaired at a cost-benefit ratio of about 1:2.5. Although, the numbers will be different under present-day land and economic conditions, there is little doubt that restoration of other than very severely desertified land can be very cost effective.

There is a huge amount of literature on all aspects of desertification and land use practices, including numerous dedicated books and many hundreds of journal articles and conference proceedings papers. Desertification is largely a land management rather than water management issue, and hence, is not a major focus of this book. The discussion of desertification herein is thus necessarily superficial. Nevertheless, it is important to recognize that desertification is intertwined with water management on many levels. Increased integration of land and water management and a proactive strategy are key methods for desertification prevention (Millennium Ecosystem Assessment 2005).

A key issue is that dryland human-environmental systems are coupled, dynamic, and co-adapting, and are the product of complex interactions between biophysical and human subsystems that are constantly changing in response to both external and internal drivers (Reynolds et al. 2007). On a large-scale level, vulnerability to desertification is generally inversely related to water availability. However, increasing the availability of water can have negative local impacts on the land. For example, overgrazing was inadvertently made worse in parts of the Sahel by the drilling of additional wells that provided year-long drinking water for livestock, which resulted in the concentration of grazing around the wells, thereby causing desertification (Dregne 1986).

Poor land management and irrigation practices are also often associated. For example, land degradation caused by salinization and water-logging is often related largely to local irrigation water management practices, particularly inadequate drainage. Declines in soil structure associated with desertification can adversely impact the water holding capacity and infiltration rates through soils. As more water runs off the land surface, less is retained in the soil and available for local recharge. Countries, communities, and individuals not having the resources (physical, technical, human, governance, and economic) to sustainably manage soil resources face similar challenges with respect to water resources.

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