DESERTS AND
DESERT ENVIRONMENTS

13

DESERTIFICATION AND THE HUMAN DIMENSION

13.1 DESERTIFICATION: INTRODUCTION AND TERMINOLOGY

Desertification refers to changes in dryland productivity, stability, and species composition. The term was first employed by Lavauden (1927) and Aubreville (1949), who used it to describe the transformation of productive land into desert as a result of human activity in Africa (Le Houérou 2002). Renewed interest in the concept of desertification resulted from a series of droughts and famines in the Sahelian region that began in the late 1960s (Herrmann & Hutchinson 2005). In its present usage, desertification is a poorly defined term, with many shades of meaning (Thomas & Middleton 1994). Inconsistency in terminology reflects an incomplete understanding of the causes and nature of change, and a lack of agreement as to the permanence and endpoints of ecosystem disruption. Desertification is difficult to determine in part because there is an absence of measurable criteria.

In general, the term *desertification* has been used to describe conditions of decreasing productivity and long-lasting, possibly irreversible, desert-like conditions. The United Nations Environment Program (1992) defined desertification as "land degradation in arid, semiarid and dry sub-humid areas resulting from various factors including climatic variations and human activities." Mainguet (1991) concluded that desertification "is the ultimate step of land degradation: irreversibly sterile land, meaning irreversible in human terms and within practicable economic limitations."

A distinction is often made between desertification and degradation. The terms desertification and desertization imply an expansion of desert-like conditions to regions that climatically would not be classified as desert. Le Houérou (2002) defines *desertization* as "irreversible arid land degradation resulting in desert-like land forms and landscapes in areas where they did not occur in the recent past." *Degradation* refers to decreases in productivity, increases in water or wind erosion, or unfavorable changes in species composition, but does not indicate that the changes are permanent or the result desert-like. The changes should be reversible with good weather and a little time. However, the use of these terms varies greatly by author.

Another way to look at desertification is as a gradational process, not an end point. Dregne (1984) suggested that landscape degradation occurs in a number of stages, from slight to very severe, with only the latter resembling a wasteland. In very severe cases, restoration may not be economically feasible. In his survey of North American desertification, he noted that the driest zones are only slightly affected, whereas the semiarid zones are most degraded. The reason for this is that very dry areas are usually too inhospitable to humans to be extensively damaged. This trend towards the greatest damage in semiarid zones is also notable in other areas of the world.

The classification system (drought, desiccation, and degradation) of Warren (1996) incorporates natural climatic variability, the ability of an ecosystem to recover from a climatic perturbation, and the degree of human intervention. *Drought* is considered a short-term and natural decline in productivity. As rainfall variability in arid regions is inherently large, dryland ecosystems and economic systems are generally geared to sustain interannual or decadal droughts with little or no damage. To avoid the difficult conditions, wild and domestic animals, as well as humans, may migrate temporarily. Vegetation may retreat from drier sites, but survive in damper ones where seed banks are retained. Recovery is complete during moister conditions. *Desiccation* is a term applied to drought over a more extended time period, which destroys natural or cultural communities. In the Sahel, rainfall began to decline in the late 1960s and never fully recovered. With respect to vegetation, desiccation may destroy local seedbeds, so that it may take many years to reestablish plant communities. Economic systems may be changed on a massive scale, and there may be significant shifts in population and changes to life style (Warren 1996). Viewed from a human perspective, *degradation* is often defined as a reduction in the land's ability to produce crops. As opposed to drought, direct intervention by humans, rather than climatic change, appears to be largely responsible, although there are probably exceptions. Degradation may also include changes to the vegetation as a result of grazing, firewood collection, or a drawdown in the water table. Water erosion, wind erosion, and salinization may singly, or in concert, play a role in loss of productivity. A change in climate is not necessary.

In many arid environments there is a positive feedback to land degradation: the demand for natural resources remains high even during drought periods, thereby causing increased pressure on the land, and the biophysical systems are unable to return to previous levels of productivity. In the Lake Chad basin, Africa, human activities have amplified water losses originally caused by drought: as rainfall for crops decreased, the amount of water withdrawn for irrigation increased, enhancing a drop in lake level.

Desertification can take place even in the absence of drought if there is increased pressure on the land by humans and livestock. A resource decline has occurred in north-central Botswana, even though there has been no decline in average rainfall over the past few decades. River discharge is insufficient for modern population levels; the water table is declining and the quality of well water is deteriorating as it becomes locally more saline; the density and species types of vegetation are failing to return to earlier levels, with an increase in unpalatable species; and bare soil is exposed, leading to wind erosion and the formation of deflation hollows (Sefe et al. 1996).

Individual countries may choose to define desertification in a way that expresses the dominant regional concerns. This definition may evolve over time. Chinese scientists in 1984 stated that "Man's excessive economic activities destroy the ecological balance of arid and semiarid areas and, as a result, blown sand and dunes have extended into these areas. This environmental change is called desertification" (cited in Ding et al. 1998). This definition focused on aeolian activity and did not directly address issues of long-term loss of biological productivity. By 1996, the meaning was enlarged to include land degradation from salination and water erosion. More recently, defined areas of desertification have included some semi-moist regions, soil erosion has been given more significance than wind-drift sand landforms, and the loss of ecological balance has been included in some Chinese definitions of desertification (Ding et al. 1998).

Although desertification influences many of the world's marginal environments, its effects appear to be most pronounced and extensive in China and Africa. It is estimated that Chinese deserts are increasing at a rate of 1560 km^2 $year^{-1}$, mainly from anthropogenic effects (Mitchell & Fullen 1994). In human terms, Africa seems to be most critically affected. During the intense drought of 1984, 40–50% of the livestock perished, 1 million people starved (Graetz 1991), and 10 million became environmental refugees (Warren 1996). Although emergencies such as these are precipitated by drought, they represent the end result of years of declining land productivity. The accumulated damage is particularly hard on the inhabitants, as Africa is already home to the majority of the world's most disadvantaged countries. Although desertification is not a new process, its effects are increasingly damaging to the dry rural economies of the region.

13.2 CLIMATE CHANGE AND DESERTIFICATION

The contribution of climate change to the desertification process is very difficult to separate from human effects, as the processes of drought and desertification often work together. Desert margins are areas of extreme variability, with decades of good years followed by short, cruel, droughts. The lack of good climatic data makes understanding long-term trends difficult. Additionally, vegetation phenology presents a major challenge to efforts to study degradation and desertification in arid lands. Phenology refers to the timing of recurring natural phenomena in the life cycles of animals and plants (such as the timing of flowering and fruiting). The climatic variation that is characteristic of deserts causes chronic vegetation stress. Complex mosaics of plant phenological states at both landscape and regional scales, and the spatial and temporal variation of live and senescent vegetation, complicate assessment of ecosystem conditions. Thus, quantitative spatial information on vegetation and biogeochemical changes associated with human land use remains elusive.

In order to address the problem of desertification, both remote sensing and field study approaches have been utilized. Many large-scale studies of drought, lacking adequate rainfall data, have used surrogate measures such as the Normalized Difference Vegetation Index (NDVI), derived from satellite data.

Advances in monitoring technology have helped modify our perspective on the nature and causes of Sahelian desertification. It is likely that the extent of desertified lands in Africa was exaggerated in early studies (Nicholson et al. 1998). Satellite imagery helped to establish that significant displacements of the desert's margin result from natural climatic variation, and that the Sahara is not marching relentlessly southward into the Sahel (see also Section 3.4.2). Over time, the boundary see-saws over as much as 300 km in response to rainfall variations. Data from satellites that carry an Advanced Very High Resolution Radiometer (AVHRR) are used to calculate a "greenness" index, which shows little long-term change in the biomass of green plants produced per unit of water ("water-use efficiency") (Nicholson et al. 1998). Although there may be some land degradation (such as a change to less palatable shrubs in overgrazed areas near villages and wells, or a change in soil texture or fertility), there appears to be no decline in overall photosynthetic activity. Thus, Nicholson et al. (1998) suggest that for the Sahel desertification is largely significant on a local scale.

In other areas, satellite imagery clearly demonstrates human activity on a regional scale, with devegetation by grazing readily apparent. From space, the international borders between Egypt (the Sinai Desert) and Israel (the Negev Desert), Namibia and Angola, and the USA and Mexico are striking owing to the differences in grazing intensities. In the visible range, the albedo of the overgrazed Sinai is 0.4, whereas that of the Negev is 0.12 (Otterman 1974; Otterman et al. 1985). Similarly, differences in grazing intensities along the border between the USA (Arizona) and Mexico (Sonora) have led to albedo changes and, possibly, to climatic effects (Balling et al. 1998; Couzin 1999). After accounting for altitude and latitude, Balling (1988) found that the higher-albedo, more overgrazed Mexican border region was on average 2.5°C warmer than the adjacent areas of Arizona. Recently, Michalek et al. (2001) examined 25 km of border and found that the differences in albedo and temperature were less compelling. They reported considerable spatial heterogeneity: in some locations, the American grasslands were more heavily grazed, and in others, the Mexican lands showed more impact. However, their research confirmed that areas with more vegetation had a lower albedo and radiant temperature than overgrazed areas.

Whereas climate change clearly affects the land surface, desertification and land-surface degradation may also influence climatic processes. Changes in land use are thought to have increased the amount of dust in the desert atmosphere (Goudie & Middleton 1992). The role of dust in changing precipitation or temperature in arid lands is controversial. Dust modifies both incoming shortwave radiation and outgoing longwave radiation, and therefore has the potential to cause either a heating or a cooling effect, depending on other factors such as cloud cover and surface albedo (Nicholson 2001). In large quantities, dust may reduce precipitation efficiency by coalescence suppression effects (Rosenfeld et al. 2001). It may also inhibit the formation of convective clouds because of radiative cooling and increased subsidence; suggesting that dust causes, rather than results from, decreased rainfall. However, dust loading of the Sahelian atmosphere has tended to follow trends in precipitation (Nicholson et al. 1998).

Although the idea is controversial, it has been argued that devegetation leads to further desiccation of the land through various biophysical feedback effects (Otterman 1974; Charney 1975; Charney et al. 1975). Charney (1975) postulated that devegetation increases the reflectivity of the ground, cooling the air that lies above it and enhancing subsidence, thus reducing rainfall. Furthermore, a reduction in trees lessens water supplied to the atmosphere via evapotranspiration. These processes, although potentially significant, are not yet fully understood (see also Sections 3.4.2 and 3.4.3). They are significant in that they imply that desertification exacerbates or causes drought through a positive feedback mechanism. The impact would depend on the degree of albedo change, which to date appears to be largely localized in extent, and therefore insufficient to cause a significant difference in rainfall (Hulme et al. 2001).

13.3 ANTHROPOGENIC CAUSES OF DESERTIFICATION

There is a closely linked, interacting set of processes that leads to desertification. Pressures on the land are related to population increases (from both high birth rates and immigration), to changing life styles which increase the demand for water and energy, to wars, to poor land-use strategies and inappropriate technology and, in some cases, to a change from a nomadic population to a more sedentary one (Abahussain et al. 2002). The resulting anthropogenic stresses include: (1) physical restructuring (land-use changes, dams, logging, earth-moving operations, watering points for cattle, dredging, artificial-lake creation, etc.), (2) the introduction of exotic species, (3) the discharge of toxic substances, (4) deforestation, overcultivation, and overstocking, and (5) changes to the hydrologic system (drawdown of groundwater, intensive irrigation, etc.) (Rapport & Whitford 1999). Manifestations of desertification include changes in speciation, water erosion (rilling or gullying), wind erosion (deflation and dust production), loss of topsoil, and soil salinization. The result is an ecosystem marked by less biodiversity, reduced primary and secondary production, the dominance of exotic species, and a lowered capacity to return to an original state.

The exact nature of human impact differs according to the nature of the desert environments and the associated political and economic systems. Impacts are broadly subdivided into those that are largely rural in nature (for example, the effects of grazing, woodcutting, or irrigation); those that involve the impact of technology on the landscape (such as transportation and communication corridors, military and off-road vehicles, and oil and mining production facilities); and urban effects (most notably, the depletion of regional water resources). This chapter briefly reviews some of these effects in the remaining sections and concludes with a case study, focusing on the environmental crisis in the Aral Sea region.

13.3.1 THE RURAL ENVIRONMENT: OVERGRAZING AND WOODCUTTING; DEVEGETATION AND BIOLOGICAL FEEDBACKS

Grazing is the most common form of land use in drylands, extending over 3.75×10^7 km^2 or 25% of the total global land surface (Dregne 1983). It affects vegetation cover and biomass, floral and faunal community structure, soil compaction and erosion, water availability, and nutrient status. The impact of livestock is a function of stocking density and management practices. Livestock tended by nomadic herders are spread in a relatively even fashion across the landscape and lead to less degradation of semiarid regions, especially grasslands, than pastured livestock. However, nomadism is increasingly uncommon and rangelands have deteriorated throughout the world. It is estimated, for example, that 94% of the rangelands of the Arab region, including northern Africa and the Middle East, have been subject to some form of desertification (Abahussain et al. 2002).

A number of recent studies suggest that overstocking can result in positive feedbacks that give rise to new ecosystem states (Schlesinger et al. 1990; Asner et al. 2003). Ecosystems tend to be stabilized by a series of feedbacks, that in undisturbed environments tend to be negative, thus maintaining the status quo. Periodic disturbances by natural events, such as fire, drought, or insect infestations are usually only a temporary setback, from which recovery is rapid. In disturbed settings, feedbacks are more likely to be positive, reinforcing the trend, and causing desertification to accelerate (Schlesinger et al. 1990; Nicholson 1998). Drought conditions enhance this latter tendency. Numerous studies suggest that arid ecosystems do not recover fully from debilitating anthropogenic stresses (Schlesinger et al. 1990; Rapport & Whitford 1999).

Overgrazing in the southwestern USA has resulted in the encroachment of woody vegetation, in particular mesquite, into former productive grasslands (Fredrickson et al. 1998). The problems, initiated following the introduction of wells and commercial cattle ranching, were exacerbated by changing fire frequency. The Chihuahuan Desert, for example, changed from historically dominant grasslands to modern shrub/dune systems supporting little herbaceous vegetation (Fig. 13.1) (Buffington & Herbel 1965). The first records of shrub and tree invasions appeared after the drought of 1891–3 (Bahre & Shelton 1993). Today, indigenous desert grasslands

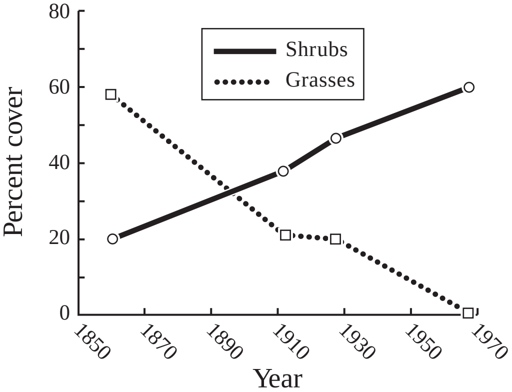

FIG. 13.1 Changes in the percentage of land area occupied by grass and shrubs, Jornada Experimental Range, Chihuahuan Desert, USA. After Buffington and Herbel (1965).

are fragmented, persisting as remnant patches amidst shrublands, shrub/grass mosaics, and coppice dunes. Deterioration of the vegetative cover has led to an increase in wind and water erosion, the formation of nebkhas, and the development of gullies.

Studies of ecosystem processes in the Jornada Experimental Range, southern New Mexico, suggest how positive-feedback processes lead to the desertification of formerly productive land (Schlesinger et al. 1990), even without long-term changes in climate. In 1885, the Jornada Plain was treeless and waterless, but covered with rich, nutritious grass (Fredrickson et al. 1998) that supported approximately 800,000 cattle and 5 million sheep. Over time, grazing increased the spatial heterogeneity of available water, nitrogen, and other soil resources, leading to shrub invasions. Domestic livestock destroyed grass cover during moderate drought and lowered the competitive potential of grasses; trampling compacted the soil and reduced infiltration; livestock dispersed shrub seeds; and greater runoff resulted in heterogeneous erosion and distribution of soil moisture, which was better exploited by shrubs.

The establishment of shrubs on the Jornada Plain tended to concentrate soil resources beneath the canopy in so-called islands of fertility, while wind and water eroded soil from the intershrub area and transported it to new locations. The bare areas between shrubs increased soil temperature, retarding the accumulation of organic nitrogen, and decreasing relative humidity. As soil-water recharge became less predictable, shrubs were better able to exploit water in deep soil layers (Schlesinger et al. 1990). Changes in species composition and nutrient conditions took place over a relatively short time frame (a few decades), even though the mechanisms that caused the changes were in place much earlier. Once the process began, it accelerated, and there has been little success in restoring grazing lands. As a result, the land today supports a small fraction of the commercial cattle herds once present (Rapport & Whitford 1999). An irreversible threshold appears to have been crossed (Schlesinger et al. 1990): the increased heterogeneity of soil resources triggered a positive-feedback mechanism that reinforced the new ecosystem state via changes in physical properties, such as soil temperature and structure, and biochemical cycles, including the availability of water and nutrients.

In Australia, the introduction of sheep and cattle into a semiarid environment also caused very rapid rates of environmental change, perhaps the greatest of any during the Holocene (Pickard 1994). Both domestic and feral herbivores have grazed the land for at least 160 years and have contributed to extensive soil erosion and reservoir sedimentation. By the 1890s, drought and overstocking had removed the feed, and up to 50% of the sheep had died from starvation (Pickard 1994). As in North America, the very high initial stocking rates were not sustainable.

The loss of herbaceous plants has also been documented in South America. In the Monte Desert, Asner et al. (2003) used imaging spectroscopy to compare ungrazed (the UN Nacunan Man-and-Biosphere Reserve) and adjacent grazed areas. Relative to the protected ecosystem, values of soil organic carbon and nitrogen storage were 25–85% lower in areas subjected to long-term grazing. The total carbon and nitrogen capital of dryland ecosystems is a broad indicator of its productivity, material cycling, and biological carrying capacity. Soil organic carbon is an integrator of ecosystem processes: a function of plant-litter inputs, microbial decomposition, nutrient dynamics, faunal activity, and hydrological processes. The loss of nonphotosynthetic vegetation (senescent, woody, or dead tissues) due to grazing has impaired carbon and nitrogen cycles that are key to the biogeochemical functioning of this arid region. The percentage cover of bare soil is also higher in grazed areas, affecting hydrological processes. In ungrazed areas, litter and standing senescent herbaceous plants act as a barrier to soil evaporation and dust generation. As grazing proceeds and the soil desiccates, only deeply rooted woody species survive, enhancing their proliferation, and the loss of herbaceous and other shallow-rooted species (Asner et al. 2003).

Woodcutting for fuel is another form of devegetation. In Africa, this is often a problem around villages, leading to a "halo effect" seen on aerial images of the Sahelian region. In North America, woodcutting has not had a particularly destructive effect on the environment, as these fuels were long ago supplanted by oil, kerosene, and coal (Dregne 1984).

13.3.2 URBANIZATION AND TECHNOLOGICAL EXPLOITATION

Although issues like grazing remain an important public concern, technological developments have created new challenges in the desert environment. Drylands are being rapidly exploited for agriculture, minerals and oil, urban development, tourism, and

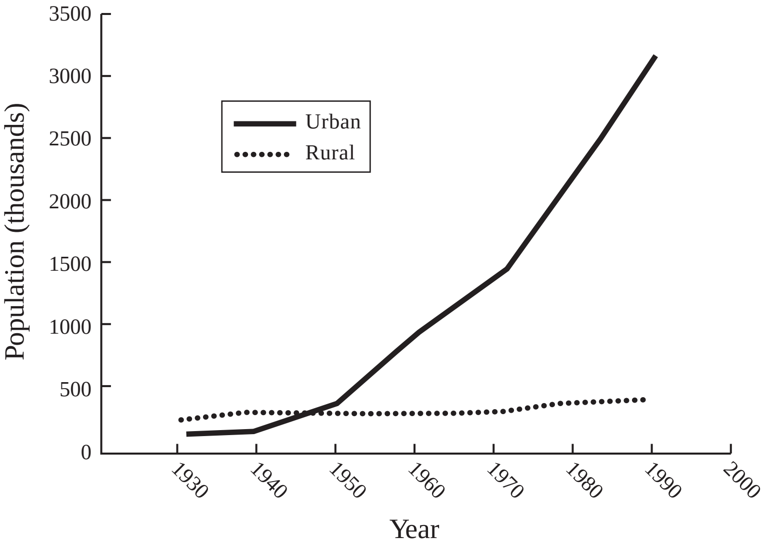

Fig. 13.2 Many of the world's deserts are undergoing rapid urbanization. This graph shows that while the rural population in Arizona, USA, has remained approximately stable, the urban population is skyrocketing. The result is air and water pollution and an increased demand for water. Groundwater pumping lowers water tables and threatens both native riparian habitats and the agricultural potential of the land. From Fredrickson, E. et al. (1998) Perspectives on desertification: south-western United States. *Journal of Arid Environments* **39**, 191–207. By permission of Elsevier.

military purposes. Impacts have included increased levels of wind and water erosion, ground subsidence due to groundwater overdraft, the spread of salinity as a result of irrigation, ecological effects consequent to the diversion and damming of rivers, the desiccation of inland lakes because of inter-basin water transfers, and rising levels of air pollution.

Rapid population growth and urbanization are putting a large stress on some areas (Fig. 13.2). In the Arab regions, 24% of the population lived in cities in 1950, around 56% in 2000, and an estimated 71% is projected to inhabit urban areas by 2030. From 1950 to 2000, the population grew from 77 million to 288 million, at an annual growth rate of 3%. In some countries, almost all of the population is urban, including Kuwait (97%), Bahrain (90%), and Saudi Arabia (83%) (Fig. 13.3) (Abahussain et al. 2002). As cities grow, they encroach on agricultural lands. To meet the greater demand for quality food in urban areas, there is a heavy use of fertilizers and pesticides, causing land and water pollution.

The demand for water in rapidly growing cities in the southwestern USA has resulted in significantly lower water tables, threatening both native riparian habitats and the agricultural potential of the land. Owing to the high cost of extracting deep groundwater, some agricultural land has been abandoned. Unfortunately, native vegetation cover does not rebound easily, owing to changes in soil texture and chemistry that result from farming. The land is thus subject to water and wind erosion that further deplete its productivity. In the deserts to the east of Los Angeles, California, suburban development is rapidly replacing arable land and agricultural water rights have been purchased to fuel urban growth.

13.3.3 OFF-ROAD VEHICLES AND MILITARY VEHICLES

The impact of off-road vehicular traffic on desert surfaces has received little attention beyond North America. In the USA, the use of off-road vehicles for recreational purposes is a small but very significant source of land degradation. Off-road driving compacts the soil, increases soil erosion, and initiates channelization and gully formation. Regulations have been issued to limit and regulate such traffic, but compliance is sometimes a problem. Some areas have been set aside as "sacrifice zones" for intensive off-road vehicle use. Ultimately these areas become so eroded that drivers seek new areas for enjoyment.

Military vehicles, such as tanks in war or combat training exercises, mechanically disrupt surfaces and

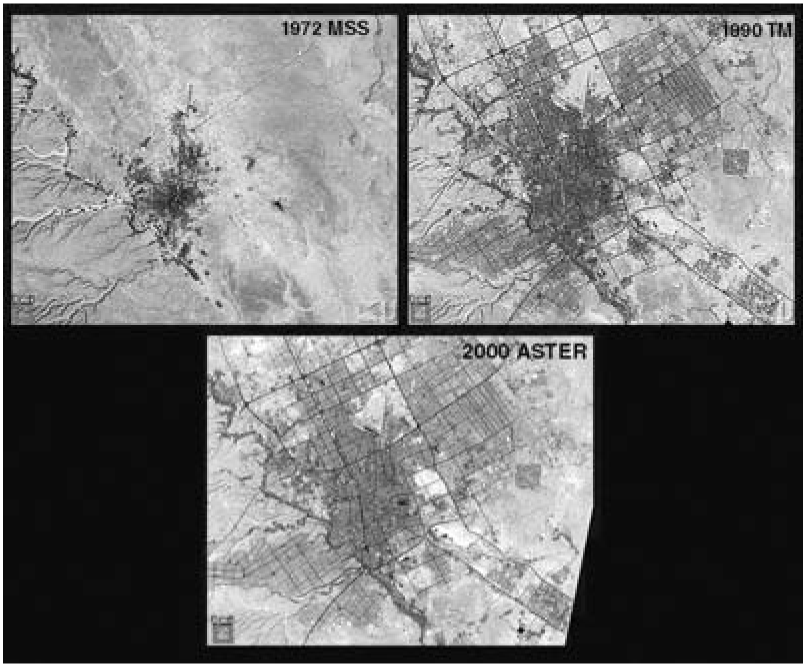

FIG. 13.3 Rapid population growth and urbanization are putting considerable stress on some areas. In Arab regions, the population has been growing at an annual rate of 3% and the population is increasingly urban. In Saudi Arabia, 83% of the population lives in cities. This image shows the growth of the national capital, Riyadh, from 1972 through 2000, during which time the population grew from about a half million to more than 2 million. Source: NASA/GSFC/METI/ERSDAC/JAROS, and U.S./Japan ASTER Science Team.

change the nature, thresholds and rates of aeolian sediment transport. During military maneuvers in the Tularosa Basin, south central New Mexico, USA, tanks eroded the margins of coppice dunes, releasing sand for transport, and enhanced interdune deflation of finer particles by breaking up the surface crust (Marston 1986).

13.3.4 INCREASES IN DUST-STORM ACTIVITY AND THE EFFECT ON HUMANS AND THE ENVIRONMENT

Changes in land use have resulted in marked increases in global dust-storm activity (Goudie & Middleton 1992). The dust commonly has negative impacts on human activities and the environment, modifying cloud formation, affecting air temperatures, degrading air quality and reducing visibility, transporting pathogens, and inducing respiratory problems (see also Section 10.5.2). Human impacts on dust generated have been reported in Australia, Africa, eastern and western Asia, and North America.

Of increasing concern in dust studies is the separation of anthropogenic and non-anthropogenic contributing factors. According to Tegen et al. (1996), 50 ± 20% of the total atmospheric dust originates from disturbed soils, including those affected by cultivation, deforestation, erosion, and changes in vegetation cover due to drought. The nature of the disturbance varies regionally. In North America, off-road vehicle use, lake drainage, and agriculture are the principal contributing factors. In Inner Mongolia, a change from nomadic pastoralism to crop cultivation and livestock rearing encouraged a threefold increase in the human population and a ninefold rise in the animal population. During periods of drought, crops fail and the sandy terrain becomes a major source of dust.

In China, issues of desertification have focused largely on wind erosion (Fig. 13.4). Desertification has enlarged the erodible area in and around the Taklimakan and Gobi Deserts, increasing dust storm activity over the past decade. It is estimated that human factors account for 78% of total Chinese wind erosion. Wind-tunnel studies suggest that erosion is accelerated by a factor of 10 by cultivation, 1.14 by overgrazing, and 22.8 by overcutting (Shi et al. 2004).

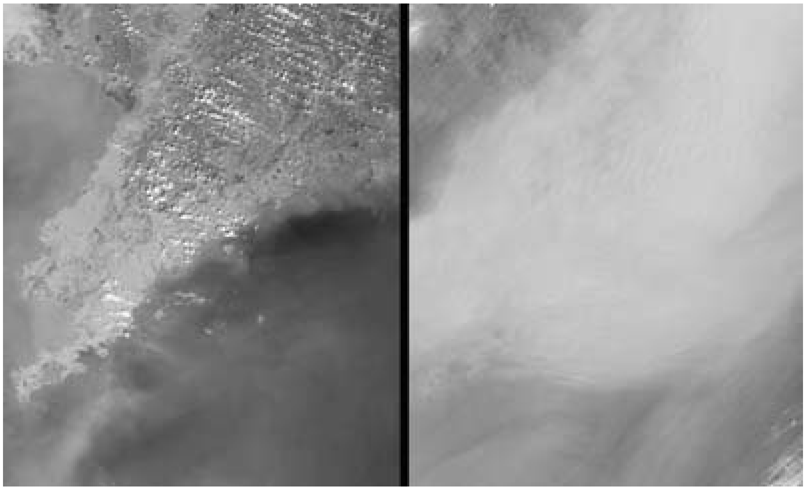

Fig. 13.4 In China, wind erosion and dust-storm activity are critical environmental concerns. It is estimated that 78% of Chinese dust is related to human causes, including cultivation, overgrazing, and overcutting. Large dust storms have effects well beyond the continent and transport not only dust, but also anthropogenic pollutants. The paired image covers the Liaoning region of China and parts of northern and western Korea. The image on the left is a clear day (23 March 2002) and is contrasted with an extremely dusty day (8 April 2002) on the right. Dust from the 2002 Asian storms was detected as far away as western North America. Source: NASA/GSFC/LaRC/JPL Team.

Large Chinese dust storms have effects well beyond the continent, drifting across the Pacific Ocean in the upper westerlies to eventually arrive in North America. Dust generated during the period 6–9 April 2001 covered vast areas of China and Mongolia, reached the Korean Peninsula on 8 April, Japan on 9 April, and North America on 12 and 13 April, reducing visibility throughout the storm's path (Liu et al. 2003). The total annual dust emissions from China range from approximately 25 to 43 million t (Xuan et al. 2000). Of this, 30% is redeposited in the immediate desert area, 20% is deposited downwind within continental China, and 50% is transported for long distances, being deposited in the oceans and islands downwind, including Japan (Zhang et al. 1997). Mass concentrations of aerosols in Beijing during a spring dust storm in 2001 were 6000 mg m^{-3}, more than 30 times the value for a normal day (Kar & Takeuchi 2004). Dust events are recorded in Seoul, South Korea, on an average of 4 days $year^{-1}$, with the frequency appearing to rise in recent times (Chun et al. 2001).

Dust that emanates from northern China threatens air quality, human health, transport, and industry in China, Japan, and South Korea. Health issues include respiratory problems and eye infections in China and South Korea, and a suspected link between dust storms and foot-and-mouth disease in South Korea. Heavy dust loads have led to traffic accidents and closed airports, including Beijing international airport. Dust particles on computer microchips threaten the South Korean electronic industry. The trajectory of spring dust events moves the air through heavily industrialized regions in China and South Korea (Chun et al. 2001). The finer dusts (<1 μm) capture anthropogenic pollutants, and nitrogen oxide and sulphur dioxide from industrial effluents enrich dust particles blown into Japan and contribute to soil acidification (Kar & Takeuchi 2004). Closer to the source, dust can have a devastating impact on livestock. The Chinese dust storm of 5 May 1993 killed 120,000 animals and that of 14–16 April 1998 was responsible for 110,000 deaths. Despite the extent and severity of Chinese dust emissions, wind erosion is often controlled on a local basis, whereas an overall national strategy is necessary.

The effect of human activity on dust storms has been well documented throughout arid and semiarid areas of the western USA. One of the best-studied sites is Owens Lake, at the southern end of the Owens Valley, probably the largest source of PM_{10} particles (particles 10 μm or less in diameter that can cause respiratory health problems) in the Western Hemisphere (Gill 1996) (Fig. 13.5). In addition to

Fig. 13.5 Dust-storm activity on Owens Lake, California, USA, has been a major health concern and impacts the visibility in several national parks. The dry lake floor is probably the largest source of PM_{10} particles in the Western Hemisphere. It was desiccated when the Los Angeles Department of Water and Power diverted inflowing tributaries of the Owens River to provide water for Los Angeles. The dust storms are most frequent in the spring and fall. Los Angeles is presently in the process of mitigating the dust emissions by a number of control mechanisms.

fine dust particles, an additional health concern is arsenic, with concentrations as high as 400 ng m^{-3} in air samples (Reid et al. 1994). Dust affects visibility in nearby national parks (Sequoia, Kings Canyon, and Death Valley), national forests, and wilderness areas, and has suspended operations at China Lake Naval Weapons Center, near China Lake. Owens Lake was desiccated in the mid-1920s after the Los Angeles Department of Water and Power (LADWP) began diverting the tributaries of the Owens River to provide water for Los Angeles. Evaporation left a 280 km^2 dry alkaline lakebed, underlain by a water table that is a few centimeters to several meters below the surface. Frequent surface flooding occurs in the winter and spring following storms. Salt crusts result from hydration and dehydration of salts brought to the lakebed surface by groundwater discharge or by precipitation/evaporation recycling of surficial evaporite deposits (Cochran et al. 1988). Efflorescent crusts on the eastern and southern sides of the lake are vulnerable to wind-blown saltating particles (St. Amand et al. 1986; Cochran et al. 1988). The largest and most frequent storms occur in the spring and fall. Wind flow in the Owens Valley is highly turbulent. Steep valley walls and variations in valley width help to create surface eddies approximately 5–9 km in diameter (Reid et al. 1994). Dust plumes are entrained 2000 m or higher over the lakebed in as little as 5 km (St. Amand et al. 1986; Reid et al. 1994). Owing to the violations of Environmental Protection Agency standards, Los Angeles has been required to mitigate the dust emissions. In a phased implementation process, three dust-control mechanisms are being used: shallow flooding, managed vegetation, and gravel. Shallow flooding involves applying water to an area until it is inundated with a few centimeters' depth or the soil becomes thoroughly saturated to the surface (LADWP 2005).

Although most human activities increase the amount of blowing dust, there are a limited number of conditions in which dust-storm frequency has decreased. In the Tedjen region of southern Turkmenistan, this decline coincided with the development of irrigated agriculture (Orlovsky et al. 2005).

13.4 WATER RESOURCES: A RURAL AND URBAN PROBLEM

Water is often the most important priority in the socio-economic development of arid regions. It limits population growth and distribution, which in deserts are concentrated on a small percentage of the land. The principal water sources are exogenetic rivers, storage reservoirs and lakes, and non-renewable groundwater resources. The reasonable allocation of these resources is constrained by a lack of good hydrologic data and an inadequate understanding of water balances and the long-term consequences of water use. Short-term and short-sighted responses to water needs and use have resulted in numerous environmental problems that are explored in the following sections.

13.4.1 GROUNDWATER WITHDRAWAL

Owing to the paucity of surface water flow in arid regions, communities increasingly rely on groundwater withdrawal to meet the needs of rapidly growing populations, which require water for basic needs, such as drinking and sewage systems or, in more affluent regions of the world, to maintain life styles transferred from more humid areas, such as maintaining suburban lawns, golf courses, and backyard swimming pools. Unfortunately, groundwater is a limited resource.

Groundwater is critical not only for human use, but also for the maintenance of plant and animal habitats. Its exploitation at rates far beyond those subject to natural recharge has caused widespread environmental damage. In the Mojave Desert, for example, groundwater withdrawal along the Mojave River for agriculture, domestic use, industry, and recreational lakes has caused the death of native riparian vegetation, the destabilization of dunes, and enhanced dust-storm activity (Laity 2003). Much of the groundwater is fossil, recharged more than 20,000 years ago, when the climate was cooler and wetter than at present (Izbicki et al. 1995). At present, the main source of groundwater recharge is winter flood flows along the Mojave River. In the 1920s, there was year-round stream flow, ponds, and over 3000 ha of tules, willows, cottonwoods, mesquite, and other plants growing in the Mojave River to the east of Barstow (Fig. 11.7) (Thompson 1929; Blaney & Ewing 1935). The mesquite that flourished in response to the high groundwater table anchored large coppice dunes. Today, groundwater, which was at or near the surface in the 1930s, is 16–30 m below the surface, well beyond the reach of vegetation. In addition to causing the death of mature phreatophytes, groundwater decline also prevents the establishment of riparian seedlings that survive the summer on underground water. Dieback of the vegetation, in combination with the strong regional winds, has caused destabilization of large floodplain nebkhas (Fig. 13.6), and actively migrating sand is encroaching on homes and agricultural

FIG. 13.6 A decline in groundwater owing to overpumping in the vicinity of the Mojave River, California, USA, has resulted in the death of mesquite that once anchored large coppice dunes. As the sand is eroded from these destabilizing dunes, it forms migrating barchans. Downwind, sand encroaches on homes (Fig. 13.7) and agricultural properties.

Fig. 13.7 Sand released from the floodplain of the Mojave River has buried this home.

properties (Fig. 13.7). Additionally, blowing dust in the lower Mojave Valley commonly obscures downwind areas. Although the Mojave River Pipeline is being constructed to bring water from the California Aqueduct to replenish groundwater within the basin, it is unlikely to bring the groundwater table back to its original level, and the short-term recovery of the environment is doubtful (Laity 2003).

Another consequence of groundwater withdrawal is land subsidence. This has been well documented in the Las Vegas Valley area, Nevada, by leveling studies conducted along survey lines, some of which were first established in the early 1930s during the construction of Hoover Dam (Lake Mead). Las Vegas is the most rapidly growing metropolitan area in the USA, with a population of over 1 million people living in an area where the mean annual precipitation is 100 mm and summer temperatures reach a maximum of 47.2°C. Evapotranspiration is between 1520 and 1830 mm per year (Devitt et al. 1992). At present, 20% of the water supply is from groundwater and the remainder from an apportionment of the Colorado River. Withdrawals of groundwater have exceeded annual recharge since 1946 (Maxey & Jameson 1948) and, although reduced after 1968, still exceed recharge by a factor of two to three. As a result of this long-term overdraft, groundwater levels have declined more than 90 m in some areas, and heavily pumped areas show surface deformation and major changes in surface elevation, with as much as 2 m of subsidence in the valley center. Much of the subsidence is preferentially focused on pre-existing faults. Spatially associated fissures have grown up to 3 m in width and 4.5 m in visible depth (Bell et al. 1992), affecting buildings, highways, buried pipelines, and electrical lines. To mitigate the problems, the Las Vegas Valley Water District initiated a program in 1988 to artificially recharge the aquifer with treated Colorado River water during the winter months. Water-conservation practices have curbed water use and the number of liters of water used per person per day has dropped annually from 1945 to the present. However, owing to the explosive population growth, the total residential use of water continues to grow (Morris et al. 1997).

13.4.2 Depletion of river flow and loss of sediment

The diversion of river water for irrigation and the employment of dams deplete or regulate river flow and change the sediment load of streams. The Colorado River once carried 18.5 km^3 of annual flow, moving 125–160 million t of suspended sediment to be deposited in the Gulf of California. Owing to intensive water extraction by the USA and Mexico, no water or sediment presently reaches the sea (Schwarz et al. 1991). The Nile River has also suffered sediment starvation owing to dam construction. Today, it only transports 8% of its former load below the Aswan High Dam. In Asia, Africa, and western North America, inland lakes have declined in area and volume owing to the depletion of inflows, as water is removed for irrigation or to fuel urban growth. One of the most severe changes has been to the Aral Sea, a region that is explored in the latter part of this chapter.

13.4.3 EFFECTS OF IRRIGATION: WATERLOGGED SOILS AND SALINIZATION

The development of large modern irrigation schemes has caused widespread soil and land degradation within and beyond desert areas. Waterlogged soils and salinization are the "twin evils" of irrigation. Increased salinity is most pronounced where irrigation raises the water table to near the ground surface, and high evaporation rates cause mineral salts to be precipitated from the water (Fig. 13.8). Attempts to reduce salinity by lowering the water table and draining and leaching the soil often alter the calcium/sodium balance to the point that soils become very alkaline. The result is a dispersion of clay particles and a breakdown of organic matter that cause a loss of soil structure and permeability, forming black alkali soils that are intractable. Increases in soil salinity and alkalinity levels reduce primary productivity and render the soil virtually sterile for all but a few specialized life forms.

The problems of salinization and waterlogging in dryland soils are global in extent. Large areas of irrigated land are affected in the Arab region, including 54% of the cultivated area in Saudi Arabia and 93% in Egypt. Yield reduction in Egypt averages 25% (Abahussain et al. 2002). Many of the irrigated lands of the southwestern USA and northern Mexico are affected to some degree by waterlogging and salinization. The principal irrigation source is the Colorado River, whose waters are allocated among seven American states and Mexico according to a complicated set of compacts, court decisions, and treaties. All of the available water is extracted and the riverbed runs dry before its terminus. The worst problems of salinization occur in the upper reaches of the Colorado River, in the Mexicali valley, and along the Pecos River in Texas (Dregne 1984). Nonetheless, there has been little abandonment of irrigated land, although there has been some decline in the economic yield. However, water that is returned to the rivers (for example, the Rio Grande) is more saline than before.

In California, much of the prime farmland is undergoing rapid urbanization, creating increased pressure on desert agriculture. Although the desert climate allows a year-round growing season, there are numerous problems, including invasions by pests and fungi (Stephens 1997). An important agricultural area is the Imperial Valley, which extends from southern California into Mexico. Water from the Colorado River is fed to the Imperial Valley via the All American Canal, and thenceforth delivered to fields through an extensive system of canals. The Colorado River has a relatively high salt content (700–850 ppm), and high rates of evapotranspiration lead to a rapid build-up of salts in the root zone. As a result, growers typically apply more water than the

FIG. 13.8 Salinized soils in arid areas reduce agricultural productivity or require the area be abandoned. Location: western China.

crop requires, with the excess leaching salts out of the soils and into a subterranean system of porous tile drains. The excess field drainage flows to the Salton Sea. Although drip-irrigated fields conserve water, they create their own set of problems. Salt accumulates in the soil and must be periodically flushed by surface irrigation. Silt from the unfiltered Colorado River water also clogs drip-delivery systems (Stephens 1997).

Salinization and changing water levels can lead to problems beyond the agricultural zone. Dam construction on the Nile River affected the water level and capillary fringe, causing the migration of salts into major archeological sites, including temples and other structures. The extension of irrigated areas on the Indus Plain has caused the disintegration of bricks at the Harappan site of Mohenjo-Daro in Pakistan by efflorescences of sodium sulphate (Goudie 1977).

An unexpected effect of irrigation may be an increase in the insect population. Irrigation provides a constant food supply for insects and results in continuous reproduction rather than a short discontinuous cycle.

13.4.4 DESERT LAKES AFFECTED BY HUMANS

Desert lakes affected by humans fall into several different categories: (1) naturally occurring lakes, such as Owen's Lake, California, the Aral Sea of central Asia, or Lake Chad in Africa, which have generally suffered from a decline in volume owing to extraction of water to meet increasing economic needs, (2) large reservoirs created by damming or diversions, designed for flow regulation, hydroelectric power generation, or irrigation (Lake Mead, Nevada; Lake Nasser, Egypt), and (3) "accidentally created lakes" such as the Salton Sea, California, sustained by irrigation waters.

The shallowing and degradation of freshwater and salt lakes and inland seas are major environmental problems in arid regions. The growth of human population, combined with climate changes that are at least partially attributable to anthropogenic pollution, exert considerable stress on closed or semi-enclosed seas and lakes. Lakes have suffered changes in their hydrologic balance (evaporation rates and inputs from surface and groundwater sources); reductions in the quality of water resources, including deterioration of geochemical balances (increased salinity, oxygen depletion); disruptions to ecosystems (eutrophication, decrease in biological diversity); and the exposure of lakebeds to the atmosphere, resulting in toxic dust emissions. The degradation of arid lake systems is exemplified by Mono and Owen's Lake, California, where water has been abstracted for long-distance transfer to the Los Angeles metropolitan area; the Dead Sea, whose level has dropped by 14 m since 1977 and whose present salinity is about 340 g L^{-1}; Lake Chad, which had shrunk to less than one-tenth of its size in 1963; and the Salton Sea, which is beset by a number of environmental problems.

The Salton Sea is located in the Imperial Valley, California. One of the most arid regions in the USA, with an average annual rainfall of 50–70 mm, it is also one of the most agriculturally productive owing to the warm climate and irrigation water supplied from the Colorado River (de Vlaming et al. 2004). The present-day Salton Sea occupies a basin that was previously occupied by a series of late-Quaternary lakes, collectively referred to as Lake Coahuilla. It was accidentally created in 1905 when Colorado River floodwaters washed out canal headgates south of Yuma, Arizona, causing the river to change course. The breach was repaired, and by 1907 the river had returned to its normal channel, but the Salton Sea remained. As its name suggests, it is a saline lake, with salinity values 30% greater than the ocean as a result of the dissolution of preexisting basin salts, high evaporation rates, and the discharge of saline tailwater from irrigation in the Imperial Valley. The lake has no outlet and today is sustained principally from agricultural drainage. However, it is plagued by elevated salinity, rising lake elevations, high nutrient loading and elevated levels of selenium from irrigation drainwater (Stephens 1997). Two rivers sustain the lake, the Alamo River and the New River. The headwaters of the New River are in Mexico, where the river receives the discharge of industrial pollutants, urban runoff, agricultural runoff, and poorly treated sewage. The Alamo River consists almost entirely of runoff from irrigation, and discharges toxic concentrations of insecticides into the Salton Sea National Wildlife Refuge (de Vlaming et al. 2004). As a result, there have been massive die-offs of fish (principally tilapia, an introduced African species) and birds, including the deaths of over 140,000 eared grebes (*Podiceps nigricollis*) in 1992. Outbreaks of fish diseases occur because of environmental stresses that include pollution, overcrowding, and high temperatures and salt levels (Fig. 13.9). Algal blooms develop in the warm summer months, stimulated by nutrients in agricultural runoff

Fig. 13.9 The Salton Sea of the Sonoran Desert has experienced massive fish die-offs owing to environmental stresses. Most of these fish, shown littering the shoreline, are introduced African tilapia. However, the lake also provides an important habitat for migratory birds. Increasing levels of salinity, selenium, industrial pollutants, and sewage have resulted in the loss of thousands of birds.

and sewage (Stephens 1997). Their death and decomposition give an unpleasant odor to the shores.

The Salton Sea National Wildlife Refuge at the southern end of the lake remains a key stop on the Pacific flyway for more than 1 million migratory birds annually and provides an important habitat for five endangered species. Measures to conserve tailwater runoff have helped to control the level of the Salton Sea, but only exacerbate the salinity problem, as tailwater had helped to dilute elevated concentrations of salt in the drainage water. Several solutions to the problems have been proposed, including evaporation ponds to concentrate the salts in one area of the sea, a pipeline to the Gulf of California to circulate water from the Sea of Cortez through the Salton Sea, and the use of agricultural waste water to create new wetlands which might act as a biological filter to partially treat the waste water (Stephens 1997).

As an illustration of the complexity of environmental issues resulting from water loss to lakes, the next section will examine the Aral Sea in central Asia. Since 1960, the lake level has dropped by about 23 m and the salinity has increased fourfold. The Aral Sea crisis is not only about water, but also air quality, nutrition, climate, the economy, and the health care system.

13.5 Case study: the Aral Sea

The Aral Sea, located in Uzbekistan and Kazakhstan, is a completely enclosed sea (lake) with a large inland catchment area (Fig. 1.2). Most of the surrounding land is desert with an annual rainfall of less than 90 mm. The Kyzylkum Desert lies to the southeast and the Karakum Desert to the south. The region has a strongly continental climate: temperatures may exceed 45°C in summer and fall below freezing in winter. The sea is a terminal basin with no outflow that is fed by two large rivers: the Amu Dar'ya and Syr Dar'ya. The Syr Dar'ya River, with its source in the Tien Shan Mountains of Kyrgyzstan, flows into the northern end of the lake. The Amu Dar'ya rises in the Pamir Mountains of Tajikistan and Afghanistan and flows into the southern shores. Input is dominated by large spring discharges of water fed by the snowfields and glaciers of the rivers' headwaters.

Flooded since the Pliocene, and reaching its maximum extent at the beginning of the Holocene, the Aral Sea has been subject to repeated major advances and recessions over the past 10,000 years, with variations even within historic time. Evidence of these fluctuations includes marine fossils, relict shore terraces, archaeological sites, and historical records. The level of the water surface has fluctuated by as much as 20–40 m in response to cyclical variations in river discharge caused by climate change and natural diversions of the Amu Dar'ya River (Micklin 1988). In 1911, when continuous instrumental observations were established, the lakebed was stable at about 53 m ASL, and remained so until 1960 (Peneva et al. 2004). During this time, it was the fourth largest lake in area on Earth. The salinity of the sea was about 1%: during periods of low lake levels, salt was precipitated in shallow bays and blown away by the wind; and during high water periods, overflows carried water to the Caspian Sea (Waltham & Sholji 2001).

Since 1960, the lake surface has shrunk from 70,000 to 25,000 km^2, a 60% decrease in area, coupled with an 80% decrease in volume (Fig. 13.10) (Micklin 1988). Towns such as Muynak, which once sat on the shores of the Aral Sea, are now more than 100 km away from an ever-receding sea. Presently, the Aral Sea is divided into two parts: the Large and Small Seas, fed separately by the Amu Dar'ya and Syr Dar'ya rivers, respectively. The Small Sea appears to be in a quasi-stable state. However, the level of the Large Sea continues to decline. Preservation of the Large Sea depends not only on the water volume delivered by the Amu Dar'ya, but also on the nature of local topographic relief. With areal shrinkage, the Large Sea has, in its turn, divided into two, nearly isolated parts; eastern and western. Water comes to the western part only through the eastern. Further water-level decline will lead to complete isolation of the West Sea from the East Sea. As a result, the West Sea, which now has more water than the East, may eventually disappear owing to evaporation: in 2000, the southern passage connecting the eastern and western basins became dry. Systematic measurements on sea level and water inflow were interrupted by the transition from control of the region by the Soviet Union to the newly independent states. Many stations that once recorded sea level have now fallen dry. Nonetheless, based in part on TOPEX/Poseidon altimeter data, Peneva et al. (2004) believe that there has been some slowdown in sea-level drop, caused by increasing discharge of groundwater into the lake.

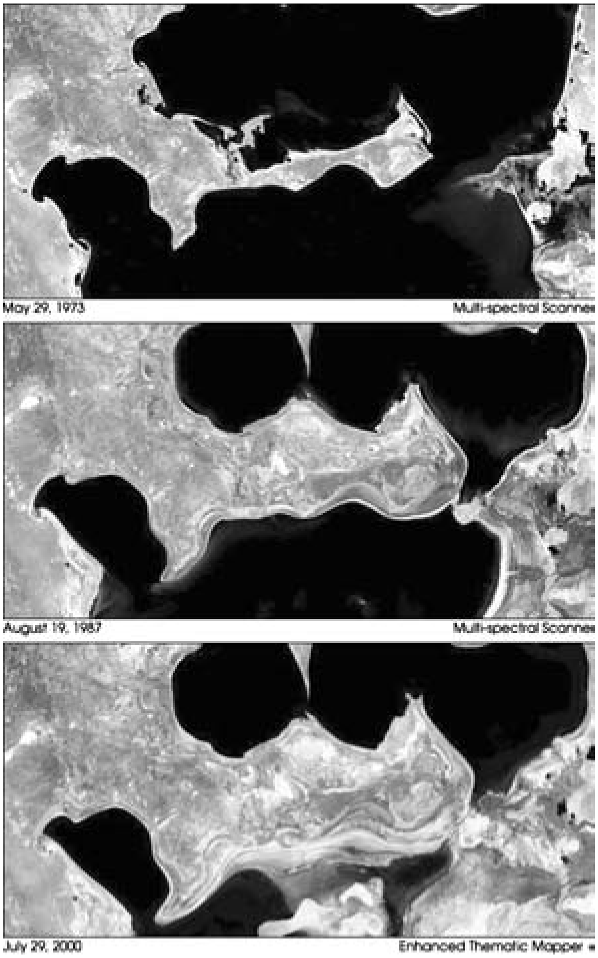

Fig. 13.10 The Aral Sea is an immense inland lake that forms a terminal basin for two large rivers, the Amu Dar'ya and Syr Dar'ya. Consumptive use of these tributaries for irrigation has led to a steady decline in the levels of the sea. Over the past 60 years, more than 60% of the lake has been lost. This image shows a sequence of images in 1973, 1987, and 2000. The exposure of the lakebed to the wind has resulted in a significant decline in air quality and a reduction in crop yields as salt-laden air is deposited on arable land. Image: USGS Eros Data Center based on data provided by the Landsat science team.

The principal cause of the decline in the Aral Sea has been consumptive use of the two main tributaries to the sea, with a steadily declining discharge of river inflow. The environmental problems began with forced cotton cultivation in the former Soviet Union, during which period inefficient agricultural organization and production, associated with water mismanagement, caused a lowering of the Aral Sea. Today, the Amu Dar'ya and Syr Dar'ya are tapped intensively for irrigation water to produce cotton and rice, with both crops requiring immense quantities of water. The irrigation canals are unlined and uncovered, and this inefficient, poorly maintained system means that little water reaches the sea. The single largest feature is the Karakum Canal, which taps into the Amu Dar'ya River and stretches 1370 km into the Turkmenistan desert (Waltham & Sholji 2001). Much of the diverted water is lost to evapotranspiration and to groundwater recharge. Many fields have become salinized and the water contaminated by salt and agricultural chemicals. Each year up to 400 km^2 of arable land is abandoned due to soil degradation.

13.5.1 LAKE-BOTTOM EXPOSURE AND SALT AND DUST STORMS

As lake surface area and volume declined, and the water table lowered, vast areas of the former lakebed (more than 1 million ha in 1990) were exposed to the winds. Most of the seabed is covered by sandy or silty sand deposits, which contain between 10 and 12% salt (Stulina & Sektimenko 2004). The exposed bottom of the Aral Sea gives rise to "white" dust storms, which combine both salt and dust (Orlovsky et al. 2005). These arise with increasingly frequency, displacing more than 43 million t of dust annually (Micklin 1988), which are deposited over a region extending from the Black Sea coast to the Arctic (Kotlyakov 1991). Dust-deposition rates south of the Aral Sea are amongst the highest in the world (O'Hara et al. 2000; Wiggs et al. 2003). The dust plumes include sodium and calcium salts as well as pesticide residues. Even though systematic spraying by pesticides has ceased owing to economic constraints, the soil remains contaminated by the organophosphate phosalone.

The dust presents a significant threat to human health for the 5 million people living in the region, and some studies suggest that diseases related to dust have markedly increased, including cancer of the respiratory tract (Micklin 1988). In addition to the Aral Sea bed, additional dust sources lie to the south and west, including the Karakum desert (Wiggs et al. 2003).

13.5.2 ECOSYSTEM DAMAGE

Prior to 1960, the Aral Sea was a vital part of the central Asian ecosystem. The delta was a splendid wetland with reed beds and lakes rich in wildlife. The reduced Aral Sea has become more saline, its biota increasingly impoverished, and its biological productivity reduced. By the early 1980s, 20 of the 24 species of fish that once inhabited the lake had disappeared, devastating the commercial fishing industry that had sustained the canneries at Aral'sk and Muynak and provided important nutritional elements to the region. The last indigenous fish disappeared in 1985 (Waltham & Sholji 2001).

The reduction in river inflow devastated the deltaic ecosystems that were once of such ecological value in a desert environment. Native plant communities which fringed delta arms, such as the *Tugay* forests, dense stands of phreatophytes mixed with tall grasses and shrubs, have been more than halved in area as floodplain inundation was reduced and the groundwater table dropped. Only 38 of the 173 animal species that once inhabited the delta have survived. In 1960, 650,000 muskrat skins were harvested annually, but by the late 1980s that number had dropped to 2400 (Micklin 1988).

13.5.3 CLIMATIC ALTERATION

Local or regional climate may be altered by the desiccation of inland water bodies. Bordering the Aral Sea, 40,000 km^2 of former lake bottom is exposed as sparsely vegetated land and evaporite deposits, changing the thermal, moisture, and radiative properties of the surface. Fluctuations in the surface area, volume, and temperature of the sea have affected the pathways of moisture into the atmosphere, decreasing precipitation (Kotlyakov 1991; E. Small et al. 2001).

Lakes similar in size to the Aral Sea are believed to influence climate over a distance of several hundred square kilometers – the well-known "lake effect" – the result of the seasonal contrast in temperatures between land and water bodies. Heat stored in a lake causes its surface temperature to lag behind that of the land, moderating both summer and winter temperatures. The reduction of the lake's size lowered its thermal capacity and increased the continentality of the regional climate, causing greater extremes of temperature (Kotlyakov 1991). Sea surface temperatures have increased by up to 5°C in the spring and summer, and decreased by up to 4°C in the fall and winter. As a result, spring and summer air temperatures are warmer, and fall and winter temperatures are cooler. Additionally, there is a greater diurnal range of air temperature, a shortening of the growing season, a decrease in relative humidity, and more severe "droughtiness" (E. Small et al. 2001). The annual net rate of precipitation minus evaporation (*P–E*) became more negative by about 15%, with the greatest changes occurring in the summer. Although the natural variability of the climate system often hinders attribution of causes of climate change, the seasonal variations in the local temperature trends are consistent with the change to a shallower, less extensive lake. Furthermore, the most statistically significant changes are clustered closest to the lake, suggesting that the observed local and regional climate changes are a result of anthropogenic modification (E. Small et al. 2001).

13.5.4 HEALTH CONCERNS

The principal direct impacts on human health in the region surrounding the Aral Sea are the salinization of the water table, pesticides in the environment and food chain, and dust storms and reduced air quality. Diseases and health conditions associated with these environmental changes include elevated rates of hypertension, respiratory conditions, heart disease, anemia, various cancers, and kidney diseases (I. Small et al. 2001b; Wiggs et al. 2003). In the area immediately south of the sea, the incidence of childhood pneumonia is the highest in the former Soviet Union. Fifty per cent of all childhood diseases in Turkmenistan are respiratory in nature (O'Hara et al. 2000). In addition, there is an epidemic of tuberculosis, probably related to the lowering socio-economic status of the residents. Other suspected adverse health effects include problems at the maternal–fetal interface (I. Small et al. 2001b).

Water quality for human consumption is poor. Overirrigation and water mismanagement have caused a rise in the water table and an increase in the total dissolved solids (TDS) in well water. Groundwater quality ranges from 0.5 to 6 g L^{-1} TDS, 20 times the average North American values. Values in the lake itself are as high as 140 g L^{-1}. Drinking water is unpalatable and more than 65% of water does not reach standards applicable to chemical contamination. Owing to the deteriorating health and economic conditions, there are now more than 100,000 "environmental migrants" who have been displaced from the region (I. Small et al. 2001a).

In order to resolve the hydrogeological, economical, ecological, and health crises in the Aral Sea region, at least 300 projects have been proposed. It is said that "if every expert brought a bucket of water, the Aral Sea would be filled again" (I. Small et al. 2001a). Proposals include restoring the Aral Sea at the expense of the Caspian Sea or north-flowing Russian rivers. However, responses to the Aral Sea situation explicitly or implicitly assume that it cannot be preserved or restored to its former level. Human responses now are geared toward diminishing the possible consequences of its shrinkage.

13.6 DISCUSSION

The topic of desertification is not a simple one. The term is ill-defined and its application varies according to author and to regional interests. At the most fundamental level, questions exist as to whether desertification exists and, if it does, how it might be defined, measured, and assessed (Herrmann & Hutchinson 2005). The topic is a fluid one, related to our changing understanding of climate variability, vegetation responses, and social processes and responses. As such, it is difficult to specify the degree to which semiarid regions have been impacted. It is likely that the process should be considered a gradational one, with severity ranked according to the chance that a region can fully recover to its original state.

The case studies discussed in this chapter suggest that, by changing the properties and scale of naturally occurring land-surface elements, human influences can significantly affect weather, climate, and the chemistry and aerosol loading of the atmosphere, at least in the short term. Larger-scale escalating effects, such as global warming, may feed back into the climatic processes of deserts. A doubling in carbon dioxide in the global atmosphere has been predicted to cause a 17% increase in the area of desert land (Schlesinger et al. 1990). The ability of some species, such as birds, to physiologically respond to increased temperatures remains doubtful (Wolf 2000). It is likely that the makeup of many desert communities will thus inexorably alter. The loss of meltwater from glacier systems will have profound effects on human, faunal, and floral communities throughout the interior deserts of Asia.

Satellite imagery suggests that, in terms of biomass loss, most desertification occurs at a local or regional scale. Nonetheless, regional environmental management practices are different enough to allow the recognition of international borders from space, including those of Egypt/Israel, Namibia/Angola, and Mexico/USA. Satellite data are of value owing to the poor rainfall records in dryland areas, but they present an incomplete measure of desertification as they provide little information on how species coverage may have changed over time. The preservation of biomass alone is not sufficient if a change occurs that causes less-desirable species to invade and proliferate in a habitat.

Positive feedbacks characterize both human and environmental systems in drylands. In southwestern North America, valuable grassland has been replaced by shrub and dune systems in an apparently irreversible change. Many other changes in deserts are irreparable over the span of a human lifetime, including the loss of valuable topsoil by wind erosion, the salinization of soil, land subsidence, the loss of riparian systems and the animal species that rely upon them, the drawdown of the water table by the mining of fossil water, the loss of vast inland seas, and the contamination of lakes and the soil by herbicides and pesticides. Unfortunately, the effects of desertification are not always limited to the immediate surroundings. Particularly in the case of dust and pollution, the impact may be global in nature, affecting the economies and public health of surrounding countries and the ecosystems of distant lands.

From a human perspective, desertification is an important issue because it heightens the effects of climatic variability (droughts) and political crises (wars). One impact is to make agricultural yields less predictable, affecting the food security of people living in a region. The result is often migration, causing suffering and death for hundreds of thousands of people.

As with other global environmental concerns, dryland degradation and species and habitat loss are accelerating rapidly within our lifetimes. Unfortunately, there are very few solid quantitative data to understand the process, particularly on a regional scale. Renewed scientific inquiry, the dissemination of such studies to a broader audience, and greater political and economic awareness of the scarcity of water and resources in the desert environment are essential if these unique areas of the world are to be preserved.