7 · Salt lakes: values, threats and future

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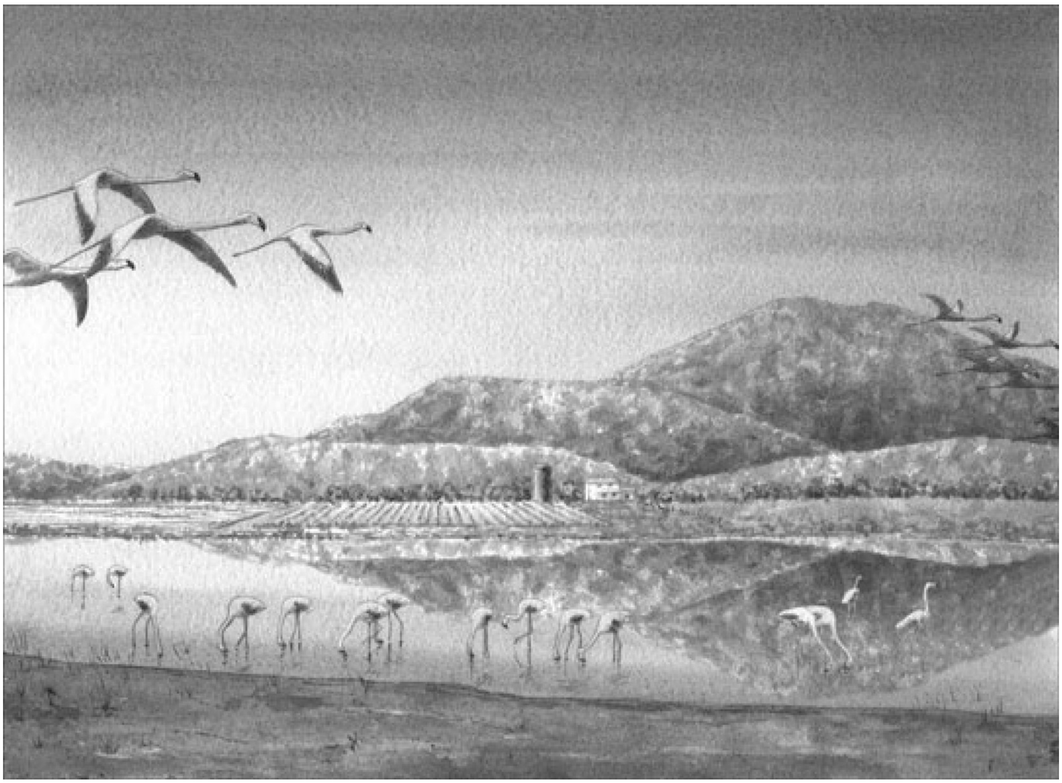

INTRODUCTION

Two types of saline water exist on Earth, namely marine waters, including brackish zones of mixing with fresh water, and epicontinental salt lakes. This chapter addresses the values, threats and likely future of salt lakes, which are here defined as permanent or temporary bodies of water with salinities >3 g per litre and lacking any recent connection to the marine environment (i.e. athalassohaline *sensu* Bayly 1967). While the use of 3 g per litre to demarcate salt lakes is somewhat arbitrary, it has come into general use and is, coincidentally, the 'calcite branch point'; that is, the salinity at which calcite is precipitated as natural waters concentrate.

The false dichotomy between marine and fresh waters embodied in the titles of institutions, textbooks and conferences obscures the fact that salt lakes are widespread and

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Fig. 7.1. Geographical distribution of major areas with saline lakes. Note that saline lakes also occur outside these areas, but at lower density. (From Williams 1998*a*.)

represent significant aquatic resources. They occur on all continents, including Antarctica (Fig. 7.1), under a range of climatic temperature regimes from the coldest to near hottest. Locally, they may be more abundant than fresh waters and, when they are, often dominate the landscape. While they are mostly confined to semi-arid (precipitation 200–500 mm per year) and arid (25–200 mm per year) regions of the world, these regions constitute about one-third of the Earth's total land area (Williams 1998*a*) and inland salt waters are not greatly lower in total global volume (85 000 km^3) than freshwater lakes (105 000 km^3) (Shiklomanov 1990). Salt lakes include the largest lake on Earth, the Caspian Sea (area 374 000 km^2), many other large lakes, lakes at the highest altitudes for any lake (>3000 m above sea level on the Altiplano of South America and in Tibet), as well as the lowest lake on earth, the Dead Sea, at about 400 m below sea level (Williams 1996). Nearly 75% by volume of inland salt waters are in the Caspian Sea. If the 15 largest lakes from both fresh and salt categories are omitted from the comparison (see data from Herdendorf 1990), salt lakes still constitute about a third of inland waters both by area and volume.

Williams (2002*a*) presented a broad overview of the development of salt lakes, threats to salt lakes, their special management requirements and their likely future status in 2025. Here, this analysis is revisited with special emphasis on their values, anthropogenic impacts and the potential for conservation in the twenty-first century. While most of the myriad impacts have long been recognized as important for individual salt lakes, their global extent, and the common trend and rapidity of degradation of a significant and unique component of the biosphere, have not been fully appreciated. Only clear recognition of the extensive damage that salt lakes are now undergoing, and of the likely result that such damage will lead to within the next 20 years, offers any hope that present trends can be changed.

VALUES OF SALT LAKES

Salt lakes encompass a diverse array of aquatic ecosystems with considerable economic and non-economic value. Among these are important scientific, ecological, conservation, cultural, recreational, aesthetic and economic values (Williams 1993*a*, 1998*a*).

Scientific value

The diversity and special characteristics of salt lakes make them of particular interest to many scientific disciplines including ecology, physiology, evolutionary biology, palaeolimnology, hydrology, geochemistry, physical limnology, microbiology and ecosystem modelling. Salt lakes range from 3 to ~300 g per kg total dissolved solids with many regional differences in their chemical composition, in contrast to fresh waters, which are mostly dilute calcium bicarbonate systems. Large regional differences in ionic composition are present due to differing catchment geology and age, and water balance; *in situ* processes determine the evolving chemical composition and salinity within individual lakes. Thus, lakes in adjacent or nearby endorheic basins (a watershed from which there is no water outflow) may vary considerably, providing unique opportunities for comparative studies.

Many early studies focused on describing the salt-tolerant biotic communities and their special adaptations to extreme environments, and this remains an active area of research for both physiologists and evolutionary biologists. The extreme environment and ranges of conditions presented by many salt lakes are of special interest to microbial researchers (e.g. Oren 2002) and studies of biogeochemical cycling. Also, hypersaline soda lakes may provide analogues to early Earth or Martian environments.

The interest of palaeolimnologists and climate researchers stems from the sensitivity of these environments to climatic and tectonic change. The climate record stored in the sediments of widely distributed salt lakes is proving instrumental in assessing past regional climate changes (see Servant-Vildary 2001; Benson *et al.* 2002).

The complex patterns of density stratification resulting from seasonally varying hydrology and thermal stratification provide unique opportunities for physical limnologists and the development of hydrodynamic models (for example MacIntyre *et al.* 1999). Their low species diversity and trophic complexity make these ecosystems attractive candidates for plankton dynamic modelling studies.

While all these different aspects of the scientific study of salt lakes are active, they are as yet not fully realized and salt lakes are still underrepresented in the scientific literature relative to their abundance. Queries of the scientific literature (ISI Web of Knowledge) show that publications with 'salt' or 'saline' as topic words constitute only 2–5% of those with 'lake' or 'lakes' as topic words during the past four decades. However, increasing awareness of the unique characteristics, values, widespread occurrence and threatened status of salt lakes are likely to result in increased scientific study in the coming decades.

Ecological, conservation and cultural values

Where salt lakes occur, they often constitute the dominant aquatic resource and thus are critical components of the natural environment. Many are among the most productive aquatic ecosystems (Melack & Kilham 1974; Jellison & Melack 1993), containing unique communities with endemic species. They are perhaps best recognized for the critical role they play for migrating and breeding waterbirds. While the critical dependence of flamingo populations throughout the world on salt lakes is widely recognized, many other waterbirds are equally dependent on salt lakes, including many species of phalaropes, grebes, gulls, pelicans and plovers. For instance, the Great Salt Lake (USA) has the world's largest staging concentrations of Wilson's phalaropes (*phalaropus tricolor*), the second largest staging population of eared grebes (*Podiceps nigricollis*), the largest breeding populations of snowy plovers (*Charadrius alexandrinus*), white-faced ibis (*Plegadis chihi*) and California gulls (*Larus californicus*), the third largest breeding population of American white pelicans (*Pelecanus erythrorhynchos*), and populations of American avocets (*Recurvirostra americana*) and black-necked stilts (*Himantopus mexicanus*) many times larger than other wetlands on the Pacific flyway. Mono Lake at the western edge of the Great Basin (USA) has the largest staging population of eared grebes, and a large population of migrating phalaropes and breeding gulls. Many other species of waterbirds use both fresh and salt lakes and thus depend on salt lakes in the absence of fresh water. The Ramsar Convention (International Treaty on Wetlands of International Importance) was initially conceived as a means of protecting critical bird habitat. Of approximately 1150 sites listed as wetlands of international importance, 150 contain salt lakes.

Many salt lakes have special significance for traditional and native cultures. For instance, in the western USA, Zuni Lake is a sacred salt-gathering site for several native American tribes, and Pyramid Lake, with its endemic and endangered Lahonton cutthroat trout (*Oncorhynchus clarki henshawi*), is also of special cultural significance. Throughout the world, artisanal salt-making or gathering is associated with hypersaline lakes and traditional fisheries occur in less saline lakes. The Dead Sea is of particular cultural significance to several world religions.

Recreational and aesthetic values

As the dominant aquatic habitat in many arid and semi-arid landscapes, birds and other wildlife congregate in large abundance at many salt lakes, making them popular tourist destinations throughout the world. Thus the lakes of the Eastern Rift Valley in Central Africa (e.g. Bogoria, Nakuru and Elmentia), and in the western USA Mono Lake, the Great Salt Lake and the Salton Sea, are all popular tourist destinations. Many lesser-known salt lakes throughout the world are increasingly becoming sites of ecotourism.

Economic values

Salt lakes have long been mined for a suite of precipitate minerals including sodium and potassium chlorides, borates, nitrates, sulphates of potassium, magnesium, calcium and sodium, calcium and sodium carbonates, and lithium chloride.

Salt-lake biota of commercial value include algal products (for example *Spirulina*), *Artemia* brine shrimps and, in lakes of low salinity, fisheries. Both frozen and dried, *Artemia* and their cysts are important to aquaculture, and large commercial enterprises have developed at major salt lakes. At Great Salt Lake, the mean *Artemia* cyst harvest from 1990 to 1996 was 1.8×10^6 kg dry mass annually with a value of US$35–110 million (Wurtsbaugh & Gliwicz 2001). In less-saline lakes, commercial and recreational fisheries are important. Of particular note is the Caspian Sea sturgeon fishery (Katunin 2000).

THREATS AND IMPACTS

Overview

Environmental impacts on the natural character of salt lakes include almost all human activities that threaten or have already had adverse effects on freshwater lakes (Chapters 5 and 6). An exception is acidification, an impact largely confined to freshwater lakes in the northern hemisphere fed by rain acidified from distant industrial emissions (Likens & Borman 1974; Chapter 5). However, salt lakes are also threatened or already impacted by other human activities less important for freshwater lakes, namely diversions of surface inflows, salinization and mining (Williams 1993*a*), and they are more susceptible to impacts from global climate change than freshwater lakes.

Global climate change

The size and salinity of salt lakes are particularly sensitive to even small changes in any component of their hydrological budgets. Unlike freshwater lakes, where minor changes in inflows, precipitation or evaporation are primarily transmitted into reduced outflows (Chapters 5 and 6), in salt lakes that lack surface outflows, the same changes are quickly reflected in changed size and salinity. While the overall effect of global warming will be a general quickening of the hydrological cycle (evaporation/precipitation), it is the combined effect of increased evaporation due to higher temperatures and the predicted large-scale regional changes in runoff and precipitation (IPCC [Intergovernmental Panel on Climate Change] 2001*d*) that will have profound consequences for salt lakes.

Global climate modelling has not developed to a state where regional trends in precipitation and runoff can be predicted with confidence. Two versions of a Hadley Centre global climate model (GCM), employing slightly different but reasonable assumptions (IPCC 2001*d*, Fig. SPM-4), illustrate this point through the large divergences of predicted runoff that occur between the two models in many regions (for example north-western USA). While site-specific predictions may be uncertain, large regional differences from current conditions are universally predicted (IPCC 2001*d*).

Of particular interest here are predicted changes in the large, endorheic basins of the world that are rich in salt lakes (Fig. 7.1). Both versions of the Hadley GCM predict decreased runoff through much of Australia. In this largely arid country, episodic lakes will fill less frequently and dry more quickly, intermittent (seasonally filled) lakes will be of shorter duration and smaller extent, and permanent salt lakes will shrink and become more saline. In situations where temporary salt lakes remain drier for longer, the biota will increasingly include species with strong abilities to disperse and tolerate long periods of desiccation, as is already the case in episodic salt lakes; in the situation where permanent salt lakes become more saline, the biota will decrease in diversity, in line with the general inverse correlation in salt lakes between salinity and biodiversity (Hammer 1986).

Other broad areas with predicted decreases in runoff include parts of arid central Asia and the Middle East, broad swaths of Africa and the Altiplano region of South America. Any effects of decreased runoff and precipitation in salt lake regions will be compounded by the fact that most climatic models predict increases in temperatures throughout much of these same semi-arid and arid regions (Hammer 1990; IPCC 2001*d*). In the Aral Sea region, for example, temperature rises of up to 6 °C by 2100 are forecast.

Of course, in areas of increased runoff and precipitation salt lakes may grow larger if inflows are not diverted. In contrast to the small (0.03–0.14 m: IPCC 2001*d*) rises in global mean sea level predicted between 1990 and 2025, lake-level rises due to regional climate change may be rapid and exceed the institutional capacity of most countries to respond quickly enough to avoid major economic losses. Within the past few decades, the levels of the Caspian Sea, Lake Van (Turkey), Great Salt Lake and Devil's Lake (USA) have already risen significantly and caused major economic losses due to inundated shore areas (Kadioğlu *et al*. 1997; Ozturk *et al*. 1997; DWR [Division of Water Resources] 2003).

The level of the Caspian Sea rose 2.5 m from 1978 to 1996, the rapid rise damaging industrial and agricultural facilities and inhabited buildings along the shore. The north-west coast of the Caspian (Atirau and Mangistau areas of Kazakhstan) suffered the most; the coastline moved up to 70 km onshore in the Atirau area, flooding *c*.1 million ha of previously agricultural land; the total cost of the damage was *c*. US$150 million (Ozturk *et al*. 1997). Flooding of oil production and transportation facilities resulted further in localized oil spills, which had environmental impacts.

Lake Van in Turkey, the 15th largest lake in the world by volume (600 km^3), rose approximately 2 m between 1985 and 1995, inundating coastal works and low-lying agricultural areas (Kadioğlu *et al*. 1997).

After a century-long decline of 6.4 m (1870–1960), the level of the Great Salt Lake (USA) returned to its historic high in just 27 years and caused substantial damage and economic loss (US$250 million) (DWR 2003). Pumps and evaporation basins were installed at a cost of US$52 million to curtail the rise. An equally rapid decline of 4.6 m over the next decade occurred (1987–1997) and the lake continued to shrink during several years of a drier climatic regime. In North Dakota (USA), the level of Devil's Lake rose by nearly 8 m over the seven years from 1993 to 1999 necessitating costly flood control and mitigation efforts (Todhunter & Rundquist 2004).

These four cases illustrate the potential economic impacts of lake-level changes that will be associated with the predicted widespread changes in regional precipitation and temperature caused by global climate warming.

The level of Lake Issyk-kul in the Tien Shan Mountains (Kyrgyzstan) recently rose 26 cm in four years (Kirby 2002), a remarkable change given that this lake is the 10th largest in the world by volume. The change is attributable to climate warming and increased precipitation, part of the rise also reflecting melting of glaciers. This example suggests regional water resources of the newly independent central Asian republics may change markedly during this century due to global climate change. As many of the major watersheds in this region are transnational, these changes are likely to result in significant political tensions and make basin-wide water management a difficult necessity.

Changes in ultraviolet radiation associated with a decrease in the concentration of ozone in the upper strata of the atmosphere (Williams 1998*b*) are potentially more injurious to salt than freshwater lakes. Ultraviolet radiation (UV-B) is rapidly absorbed in the upper layers of water in lakes but, if lakes are shallow, as many temporary salt lakes are, little absorption can occur before the biota are affected. Lake Cantara South, a shallow salt lake in South Australia, is one example of many that would likely be affected in this way.

In addition to changes in temperature and runoff/precipitation patterns, salt lakes will be affected by the suite of impacts from global warming identified for freshwater lakes (Magnuson *et al*. 1997; Poff *et al*. 2002), including changes in timing and depth of seasonal mixing, increased water temperatures and productivity, and in some cases bottom-water anoxia.

Surface inflow diversions

Global population increase and economic development in arid and semi-arid regions of the world have led to increasing freshwater scarcity to a degree which may become a crisis early this century (Shiklomanov 2000). While global climate change will necessarily impact salt lakes throughout the world, the most serious impact to permanent salt lakes is likely to be from continuing and increased diversions for irrigated agriculture. Since diversions alter the hydrological budget, and salt lakes respond quickly to such alterations, inflow diversions invariably cause a rapid decrease in lake volume and the physical and chemical features contingent upon volume, especially salinity (Williams 1993*a*). Salt lakes throughout the world are being desiccated due to increases in irrigated agriculture. Apart from several well-known examples (for example the Aral Sea, the Dead Sea, and Mono Lake in

California), the worldwide extent of salt lake desiccation has received scant attention.

CENTRAL ASIA AND NORTHERN CHINA

Inflow diversions have been greatest and had the most profound environmental effects for the Aral Sea (Micklin 1988, 1998; Williams & Aladin 1991). Prior to 1960, the annual volume of inflows from the rivers Syr and Amu Darya was 56 km^3; after diversions for greatly expanded irrigated agriculture, the annual average inflows in the decades that followed were 43 km^3 (1961–70), 17 km^3 (1971–80) and 4 km^3 (1981–90) (Letolle & Mainguet 1993). These massive diversions of water used particularly for cotton and rice cultivation, led to a >15-m drop in the surface level of the Aral Sea after 1960 and an increase in salinity from 10 to 28–30 g per litre when the sea split into two basins in 1989. The water level of the Large (southern) Aral Sea has continued to fall and salinities increased to ~70 g per litre by 2002. In 1960, the fish fauna consisted of over 20 native and introduced fishes while the invertebrate community included >200 species. After parting into the Northern and Large Aral Seas, only seven species of fish, 10 common zooplankton species and 11 common benthos species were present (Plotnikov *et al*. 1991). Increased salinity of the Large Aral Sea has resulted in complete elimination of the fishes and 11 of the invertebrate zooplankton species; only the widely euryhaline rotifer *Brachionus plicatilis* has survived. However, three new halophylic species appeared apparently through aeolian transfer, namely the cladoceran *Moina mongolica*, the brine shrimp *Artemia salina* and the infusorium *Fabrea salina*. Of 10 zoobenthic species, only two euryhaline species of gastropods (*Caspiohydrobia* spp.) and one euryhaline ostracod (*Cyprideis torosa*) remain.

In addition to the total collapse of the Aral Sea fisheries and the towns dependent on them for livelihood, a whole suite of environmental impacts has been associated with desiccation of the Aral Sea including toxic dust-storms originating on the exposed lake bottom, deterioration of the large deltaic ecosystems of the Syr and Amu Darya, drier and more extreme climate, water-table lowering and increased desertification (Micklin 1988). Furthermore, inefficient irrigation practices have led to severe salinization problems throughout the region with 10–15% of irrigated lands in the Kyzyl Orda Oblast being rendered unsuitable for agriculture each year (UN Country Team 2004).

Irrigated agriculture has led to the decline of salt lakes throughout the arid regions of central Asia from Tuz Lake in Turkey to northern China. Kazakhstan's two Ramsar sites (lakes of the Lower Turgay and Irgiz, and Tengiz Lake) are both threatened by water diversions (Wetlands International 2002). Also, Kazakhstan's largest lake, Lake Balkash, has shrunk during the past 20 years, presumably due to upstream agricultural diversions. In northern China, the desiccation of lakes has been especially pronounced (Tao & Wei 1997). In the 1950s, there were 52 lakes over 5 km^2 in area in Xinjiang province, with a total area of 9700 km^2, but the area had decreased to 4700 km^2 by the early 1980s. Lop Nur (3000 km^2) dried in 1964, Lake Manas (550 km^2) in 1960, Lake Taitema (88 km^2) in 1972 and Lake Aydingkol (124 km^2) in the 1980s. Lake Ebinur (1070 km^2) and Lake Ulungur (745 km^2) have respectively been reduced to one-half and one-tenth of their original size since the 1950s. On the Alxa Plateau of Inner Mongolia, Gaxun Nur Lake (262 km^2) dried in the 1970s and the Sogo Nur Lake in the 1980s. In Hubei Province of China, the number of lakes over 0.5 km^2 in area has decreased from 1066 to 309.

AUSTRALIA

Lake Corangamite in south-western Victoria (Australia) has shrunk due to diversion of its major inflowing stream (Williams 1995). By 2002, salinity exceeded 100 g per litre, with marked reduction in its biotic diversity. Although restoration of this Ramsar site is possible and an enquiry has been held, its desiccation has continued. Lake Eyre would have been affected by irrigation plans in its Queensland catchment, but these plans were dropped. Lacking other large terminal salt lakes, the threat of diversions is less in Australia than in other endorheic regions of the world.

However, salinization is a major problem in agricultural areas, and already 30% of such lands are degraded, mainly in south-western Western Australia and in the southern Murray–Darling Basin (Chapter 4). Nationwide, 80 important wetlands are already affected and this number is predicted to rise substantially by 2025. In the wheat belt of Western Australia, 75% of waterbirds have declined in abundance and some 200 aquatic invertebrates are likely to become regionally extinct. The salt waters, both in modified freshwater wetlands and in new sites, are even more depauperate than natural salt waters, and in some areas are being invaded by alien *Artemia* sp., instead of the endemic *Parartemia* spp. However, in the Murray–Darling Basin, some of the evaporation basins, provided to rid the land of salty irrigation wastewater, support many waterbirds.

AFRICA

The demand for fresh water is expected to increase markedly throughout Africa due to increased human population and economic development. In addition to the 14 countries already considered water stressed (<1700 m^3 of renewable water resources per caput), another 11 countries are expected to become water stressed by 2025 (Clark 1999; Johns Hopkins 1998). While some of the most spectacular salt lakes in the East African Rift Valley (for example Bogoria or Nakuru) are not currently threatened by diversions, others have shrunk due to diversions. For example, Lake Abe on the border of Ethiopia and Djbouti has shrunk by 67% since the 1930s, as a result of irrigated agriculture in Ethiopia (UNEP [United Nations Environment Programme] 2000*a*). In this and many other cases, the transnational character of major river basins throughout Africa makes integrated basin-management difficult. With only 6% of its cropland currently under irrigation, water diversions for irrigated agriculture will certainly increase in all of the endorheic basins. In Malawi, the large shallow saline Lake Chilwa provides one-quarter of the fish caught in Malawi but faces threats of water abstraction within the basin and reclamation of nearby swamps for agriculture or irrigation reservoirs. These swamps are particularly important as fish refugia in times of low lake levels during dry periods when the lake nearly dries.

MIDDLE EAST

Much of the Middle East consists of arid and hyper-arid regions, the dominant surface water resources being the Jordan, Tigris and Euphrates Rivers. The Arabian Peninsula is completely lacking in major river systems and contains very few permanent salt lakes. Salt lakes in the interior consist mostly of episodically flooded *sabkhas* (salt flats), thus water diversions are not economically feasible. However, the level of the Dead Sea at the terminus of the Jordan River has dropped over 13 m since 1981 (Oren 2002) because of upstream diversions in Jordan and Israel for irrigated agriculture. As the Dead Sea has been extremely hypersaline for many centuries, the loss of ecological resources associated with its desiccation is much less than that observed when less saline lakes are desiccated. However, the lake has significant cultural and recreational values; several proposals involving diversions from the Red Sea have thus been made (Beyth 2002) and may be acted on. Iran contains a number of large and productive salt lakes, of which Lake Urmia (483 000 ha) is the most notable with its large populations of pelicans and flamingos and *Artemia* fishery (Scott 1995). While the Mahabad Multipurpose Drainage and Irrigation Project reduced freshwater discharge into the marshes at the south end of the lake in the early 1970s, the overall effect was lessened by return flows. A more serious threat is likely to be pollution from nearby large cities and toxic chemicals used in agriculture. In eastern Iran, Hamun-e-Saberi and Hamun-e-Helmand, two large semi-permanent lakes, spanning from fresh to hyposaline, have been impacted by diversions for irrigated agriculture on streams in neighbouring Afghanistan. Afghanistan has only a couple of notable salt lakes, one of which (Ab-i Istada) is threatened by diversions.

SOUTH AMERICA

In South America, salt lakes lie predominately in the Bolivian Altiplano, its northern Peruvian extension and the pampas of Argentina. The former contains many ephemeral saline lakes and playas (*salars*) (Hammer 1986) that are not suitable for development of irrigated agriculture. However, Lake Poopo at the terminus of the Desaguadero River, which flows from Lake Titicaca, may be impacted by planned water diversions. In Argentina, the large and variable Mar Chiquita (7000 km^2 in 1987) and the smaller Lagunas y Esteros del Ibera (245 km^2), both Ramsar sites, are threatened by diversions. However, at present most water development in South America is focused on the large exorheic river systems.

NORTH AMERICA

All large salt lakes in the Great Basin of the USA, except the Great Salt Lake, have experienced marked declines because of diversions for irrigated agriculture; these include Mono, Walker, Pyramid, Owens and Winnemucca. The large salt lakes Owens and Winnemucca were completely desiccated in the twentieth century. Before inflow diversions led to its demise, Winnemucca Lake was about 40 km long and 5 km wide and had a salinity of 3.6 g per litre in 1884 (Clark 1920). The lake dried following diversions from the Truckee River and is now merely a flat expanse of dry land next to Pyramid Lake. Owens Lake was about 24 km long, 16 km wide and 10 m deep. Between 1890 and 1914, its recorded salinity ranged from 16 to 214 g per litre (Clarke 1920). Beginning in 1913, diversions of water from the lake to provide domestic supplies to Los Angeles led to its complete desiccation by 1926. The exposed lakebed is one of the single largest sources of particulate aerosols in the USA (Cahill *et al.* 1996), and approximately US$100 million has been spent on mitigation measures aimed at controlling the dust. Mitigation includes shallow ponds, event-oriented sprinklers and establishment of salt grasses.

The level of Walker Lake (Nevada) fell by 40 m from 1882 to 1996 and salinity increased from ~3 to 13 g per litre as it shrank from 280 to 140 km^2 (Beutel *et al*. 2001). Following a brief respite in 1995 as a result of above-average runoff, it continued to decline. In 2004, salinities exceeded 15 g per litre (R. Jellison, unpublished data 2004), and these are considered to exceed the critical threshold for successful reproduction of tui chub (*Gila bicolor*), the primary prey of the endangered Lahontan cutthroat trout. Thus, the recreational fishery may collapse in the near future.

Following the initiation of water diversions in 1941, Mono Lake's level declined by 14 m and its salinity doubled from 48 to about 95 g per litre. At Pyramid Lake, water levels have fallen by about 21 m since 1910 and its salinity increased to 4–5 g per litre. However, both these lakes have management plans in place to prevent further desiccation (see below).

In all of these lakes around the world, increasing salinities have significantly altered the biotic communities. The biological effects of increased salinities depend largely upon the original salinity. They have usually been greatest when the original salinity was low, and least when it was hypersaline. Thus, the effects of the 20 g per litre increase in Lake Corangamite were significant and led to the almost complete disappearance of fish, amphipods, snails and *Ruppia* (ditch grass, Potamogetonaceae), with consequent effects on the associated avifauna that fed on the lake (Williams 1995). Any further increases in the salinity of Walker Lake are expected to lead to collapse of the recreational fisheries. Conversely, the >100 g per litre increase in the Dead Sea had little effect on the lake biota and fundamental processes (Williams 1993*b*). With few exceptions, it is expected that permanent salt lakes with defined surface inflows will be impacted seriously during the developing freshwater crisis in the arid and semi-arid regions of the world.

The effects of falling water levels are not restricted to gross chemical and biological effects; many other physicochemical and environmental changes also follow. They may include changes to the local climate, additional dust blown from exposed lakebeds, falling groundwater levels and the loss of islands, and consequently other effects, as for example in the Aral Sea (Letolle & Mainguet 1993).

Groundwater pumping

Alone or in conjunction with surface diversions, groundwater pumping for agricultural purposes threatens many shallow salt lakes that are essentially surface 'windows' of shallow water tables (Williams 1993*a*). While in the past, this impact has generally been local in nature, increased groundwater pumping in many arid regions during the past several decades has resulted in greatly lowered water tables over large areas (Chapter 3) with the concomitant desiccation of salt lakes. This is particularly true in northwest China, the Middle East and Mexico. Most of the shallow permanent and temporary salt lakes in central Mexico have already disappeared because of over-pumping of groundwater for irrigation, and other deeper lakes have shrunk rapidly (Alcocer & Escobar 1990). In north and central Mexico, four crater lakes in Valle de Santiago (Guanajuato) have undergone rapid desiccation (Alcocer *et al*. 2000). San Nicolás de Parangueo and Cíntora are already dry (the former in 1979 and the latter sometime between 1980 and 1984), while Rincón de Parangueo and La Alberca are nearly dry. The original water level in Rincón de Parangueo and La Alberca shows the lakes to have been around 50 m deep. La Alberca was 35 m deep in 1985, 10 m deep in 1995 and only a few centimetres deep in 2002. Rincón de Parangueo was 7.5 m deep in 1995 and is now almost dry. Many temporary salt lakes in central Spain are similarly threatened or affected.

In Algeria, *foggaras* (unique systems of subsurface irrigation conduits totalling 1377 km in length), associated oases and salt *sabkhas* are threatened by lowered aquifers because of the large volume of groundwater pumped.

The greatest threat to salt lakes from groundwater pumping may be the increased demand on surface waters as aquifers are depleted. A significant portion of increased world agricultural output over the past 50 years has depended on over-drafting of groundwater aquifers in countries such as China, India, USA, Pakistan, Mexico, Iran, South Korea, Morocco, Saudi Arabia, Yemen, Syria, Tunisia, Israel and Jordan (Chapters 1 and 3). Decreases in agricultural output may occur as major aquifers underlying newly developed agricultural areas in these countries become depleted; signs of this are already present, especially in China (Brown 2003).

Secondary salinization

While one of the effects of surface-inflow diversion from large salt lakes is inevitably increase in the lake salinity, clearance of the natural vegetation and other land-use changes within catchments also increase salinity (Williams 2002*b*). The subsequent salinization involves the mobilization of salts dissolved in groundwater. The salts move towards the surface as the water table rises when the amount of groundwater transpired by deep-rooted plants falls (or after the addition of excess irrigation water to groundwater), and once near the surface, capillary action brings them to the surface. There, evaporation leads to salt deposition. Leaching of deposits, if within the catchment of a salt lake, adds to the natural salt inflows to the lake. This process is referred to as secondary (or anthropogenic) salinization to distinguish it from the process of salinization involved in the natural development of salt lakes. The impacts of secondary salinization are not confined to salt lakes, but are a major threat to all natural water resources in semi-arid and arid regions of the world (Williams 1999, 2001, 2002*b*).

The threat of secondary salinization appears largely to have been underestimated in most dry land countries, Australia being an exception. The extent to which inland waters have already been altered by additional salt inflows is uncertain, but Gleick (1993*b*) estimated that globally, *c.*10 million km^2 of land have already been affected. Secondary salinization has disturbed the natural hydrological and salt cycles in many arid regions, with many salt lakes becoming more saline, and many freshwater lakes turning saline (Williams 2001). In addition, a large number of unnatural salt lakes (so-called evaporation ponds or discharge basins) have been constructed in irrigated areas as basins into which agricultural saline wastewater is discharged (Evans 1989).

The Salton Sea (California, USA) provides an unusual example of salinization of an episodic salt lake now being used as a discharge basin. Deltaic geomorphological processes have caused the Colorado River to alternate outflows between the Salton Basin and the Gulf of California over the past 10 000 years. The basin was dry in 1905 when floods breached a dyke and redirected the entire flow of the Colorado River into the basin, creating the modern Salton Sea. Following the repair of the breach in 1907, the lake shrank due to evaporation, and salinity increased to ~40 g per litre by the 1920s, at which time wastewater from irrigated agriculture largely stabilized the lake level for the remainder of the twentieth century (Schroeder *et al.* 2002). In addition to recreational values, the lake provides critical habitat for large numbers of breeding and migratory bird populations, especially as a result of the large loss of wetlands in western North America during the twentieth century (Shuford *et al.* 2002). However, the salt load from agricultural inputs is resulting in an annual increase of ~0.3–0.4 g per litre in lake salinity, and threatens the lake's fishes and other biota. Planned mitigation efforts include desalination of inputs and reduction in lake size through construction of a dam across the middle of the lake.

The effects of secondary salinization brought about by human activities on salt lake catchments are chemically similar to those brought about by inflow diversions, that is, increases in salinity and the consequences of this. Direct physical effects are few because, unlike flow diversions, secondary salinization is not associated with large changes in lake volume and water level. It is, nonetheless, equally if not more important since it has a major impact upon temporary salt lakes and is geographically more extensive. Moreover, it has increased the number of salt-water bodies and altered natural hydrological patterns.

Mining

Several human activities physically disturb the beds of dry salt lakes, and of these, mining is the most important, especially for temporary lakes, which are particularly vulnerable when dry. Mining is often for halite, but minerals mined also include trona, calcite, gypsum, borax and, more recently, lithium and uranium salts (Reeves 1978). These minerals are frequently mined from surface deposits, and mining involves the construction of levee banks, causeways and other structures that physically damage the structure of the lake (Williams 1993*a*). Rarely, if ever, is such damage repaired after mining has ceased. Where mining involves subsurface deposits, large quarries referred to as voids, as well as holding reservoirs, may be constructed on the lake bed. In some cases, subsurface mining on salt lakes may be for minerals that are not directly associated with the salt lake as evaporites, clastics or authogenics but are located deep beneath the bed of the lake. Mining is not confined to deposits on or beneath the dry beds of temporary salt lakes. Many minerals are mined from salt-lake brines and a few from beneath the beds of permanent salt lakes, drilling for oil beneath the Caspian Sea providing the most notable example (Kosarev & Yablonskaya 1994).

Apart from the physical disturbance, mining may have impacts on salt lakes in other ways, particularly by adding pollutants. Oil spills from mining rigs in the Caspian, the discharge of mine wastewaters and the location of mine spoil dumps (from which pollutants leach) adjacent to salt lakes provide examples (Dumont 1995).

Mining can also lead to the development of unnatural saltwater bodies in temperate regions. The moderately salt lakes or 'flashes' in Cheshire (UK) are the result of land collapses over salt deposits mined from underground. Quarries containing salt water in Germany developed when the pumping of salt groundwater intrusions stopped (Bohrer *et al*. 1998). In semi-arid regions, the construction of solar salt ponds (from which salt is obtained by the evaporation of seawater or salty groundwater) provides a unique example of unnatural saltwater bodies that have been constructed to 'mine' salt from the sea or underground. Activities other than mining that physically disturb the beds of salt lakes include the construction of canals and other structures designed to drain salt lakes, and in the USA the use of dry lakebeds as racetracks.

The limnological effects of physical disturbance to (dry) salt lakebeds by mining are little known. Levees, causeways and canals will clearly impede the free surface movement of water across the bed of the lake, but the consequences of this are unknown. They may not be significant. In this context, the biota of salt lakes, especially episodically filled bodies, comprises both an aquatic component, present when the lake contains surface water, and a terrestrial component, restricted to the bed of the lake when it is dry. What is clearly significant, however, are impacts on the appearance of the lakes; affected lakes lose much of their aesthetic appeal. Tailing dumps, mining voids, vehicle tracks and other impacts associated with both surface and deep mining at salt lakes likewise detract from and destroy a core part of their aesthetic appeal, namely the visual relief provided by a pristine landscape in a world much altered by humans.

Pollution by mining can have various effects depending upon the pollutants involved. Heavy metals leached from mining dumps act in the same way as toxicants do in all aquatic ecosystems; both biodiversity and biomass are reduced (Moss 1998). Salt wastewater has less profound effects, but will at least alter the natural pattern of salt loading. Hydrocarbons released accidentally by mining for oil in the Caspian Sea are already having an injurious effect on the economically important sturgeon in the lake (Kosarev & Yablonskaya 1994; see below).

Of actions other than mining that disturb salt lakes in a direct physical way, the most important is drainage, which leads to total loss, as occurred in Lake Texcoco, on the bed of which lies Mexico City (Alcocer & Williams 1996). Canalization, dyke and levee construction, road-building, drainage and landfill have all but obliterated the original lake.

Pollution

Inorganic plant nutrients appear not to be major pollutants in salt lakes, though exceptions occur (Williams 1981). For example, Farmington Bay of the Great Salt Lake has become eutrophic as a result of excess nutrients in runoff from urban development around Salt Lake City. Generally more significant is pollution through inputs of agricultural wastewater (often saline), pesticides in runoff and a variety of organic and inorganic wastes from domestic and industrial sources. Because salt lakes are usually regarded as water bodies of little value, they are often also used as sites for dumping solid wastes.

The pollution threats to salt lakes are often assumed to be broadly similar to those pertaining to other lakes (Williams 1993*a*). All of the sorts of pollutants discharged into fresh waters are also discharged into salt lakes, either directly or indirectly via their inflows. Most of the pollutants now present in the Aral Sea, for example, came from the Syr and Amu Darya (Letolle & Mainguet 1993) and many pollutants in the Caspian Sea come from the Volga River (Kosarev & Yablonskaya 1994).

In nearly all instances where wastes are discharged to salt lakes, it is assumed that the lakes in question will respond in fundamentally the same way as freshwater lakes and rivers (Chapters 2, 5 and 6). Often, the same discharge criteria are used by environmental protection agencies for both salt and freshwater lakes (Williams 1981), however account needs to be taken of the fundamental hydrological differences between them. Salt lakes are more or less closed hydrological systems and thus accumulate and biomagnify many pollutants to a much greater degree than do freshwater lakes and rivers (Williams 1981), and salinity may modify the toxicity of certain pollutants. The effects of pollutants in salt lakes may not be confined to the aquatic biota *sensu stricto*. The accumulation of selenium salts in evaporation ponds constructed to manage salt wastewaters in the western part of the USA provides an example. Selenium was soon transmitted to waterbirds that used the ponds; primary effects were mortality and deformity of adult birds (Schroeder *et al*. 1988).

Overfishing

As with freshwater lakes, salt lake fisheries are often overexploited. Of particular note is the near collapse of the sturgeon fishery in the Caspian Sea. At peak harvests in the 1970s (27 400 tonnes per year), the Caspian Sea provided up to 90% of the world's landings but subsequently declined to *c*.3000 tonnes per year (Ivanov *et al*. 1999). The fishery management problems of salt lakes are similar to those of other lakes and will not be discussed further here, except to note that as salt lakes become more saline, introductions of more salt-tolerant fishes are often attempted with varying degrees of success (for example in the Aral Sea: Aladin & Potts 1992; and the Salton Sea: Riedel *et al*. 2002).

Biological disturbances

The biota of many salt lakes has been unnaturally disturbed by the introduction of exotic species. Fish of recreational interest have been introduced into many moderately salt lakes (e.g. several lakes in Canada and Bolivia, and at least one in Australia (Lake Bullen Merri, salinity about 8 g per litre): Rawson 1946; Hammer 1986). In some cases, fish populations became self-sustaining and of commercial value, as in the Aral Sea, where, beginning in 1927, at least 21 species of fish were, either deliberately or accidentally, introduced, mostly from the Caspian, Baltic and Azov Seas and Chinese lakes (Zenkevitch 1963). All have now become extinct following the rise in salinity of this lake. In the Caspian Sea at least nine of the species introduced have survived (Kosarev & Yablonskaya 1994).

Many invertebrates have been introduced to moderately salt permanent lakes. Thus, of 18 invertebrate species introduced into the Aral Sea either accidentally or deliberately from 1927 onwards, mostly from the River Don and the Caspian and Azov Seas, over 10 established successful populations (Aladin *et al*. 1998). They disappeared when the salinity of the Aral Sea rose beyond their halotolerance. In the Caspian Sea, most introduced invertebrate species appeared after the opening of the Volga–Don Canal in 1954. Over 10 such species are known to have acclimatized to conditions in the lake, with two, the coelenterate *Aurelia aurita* and the ctenophore *Mnemiopsis leidyi*, considered highly likely to have significant impacts on some fish populations (Ivanov *et al*. 2000).

Temporary and/or highly salt lakes are unsuitable habitats for fish and relatively few invertebrate introductions into them have been attempted. However, the widespread and largely *ad hoc* importation of species of *Artemia* brine shrimp into coastal solar salt pans to reduce unwanted algal growths poses a serious threat to the biota of nearby natural salt lakes (Geddes & Williams 1987). Little if any attempt has been made to control these importations, in spite of the hazards involved (Geddes & Williams 1987). A species of *Artemia* from coastal salt pans in Western Australia has recently invaded inland natural salt lakes (B. Knott, personal communication 2000).

Other forms of biological disturbance apart from exotic introductions exist, for example predation by terrestrial predators on bird species dependent on salt lakes for breeding and food. As the Aral Sea shrank following inflow diversions, many small islands in the south-east of the lake became peninsulas, so allowing predators access to migratory and resident waterfowl populations (Williams & Aladin 1991). Also, the recent expansion of silver gull (*Larus novaehollandiae*) populations in Australia, following the increase and expansion of town dumps which are used as feeding sites by the gull, has increased predation pressure on the banded stilt (*Cladorhynchus leucocephalus*) (Robinson & Minton 1990).

For the most part, the effects of introduced exotic species on the biota of salt lakes are unknown. Introductions are usually made in an *ad hoc* fashion, and any subsequent investigations are more concerned with determining the extent to which introduced species have acclimatized than with any adverse impacts on native species. Nevertheless, there is some evidence that introduced species which become acclimatized may replace native species. In Australian solar salt ponds, for example, introduced *Artemia* species, perhaps because of their ability to produce haemoglobin at high salinities and hence withstand low oxygen concentrations, seem to be able to displace the native *Parartemia* brine shrimp species, at least in the highly salty ponds as in western Australia (Mitchell & Geddes 1977).

Interactions between introduced and native species may not necessarily be confined to those in related taxonomic groups. The most serious effect of introduced *Aurelia aurita* and *Mnemiopsis leidyi* in the Caspian Sea is likely to be their competition for food with planktivorous fish, which may subsequently decrease in abundance (N. V. Aladin, unpublished data 2001).

Other catchment activities

Soil erosion, increased sediment loads and changes in runoff patterns can be the result of other catchment activities, including overgrazing by cattle and sheep and excessive clearance of the natural vegetation (Williams 1993*a*). After rainfall, runoff from overgrazed and/or cleared catchments is usually larger in volume but takes place over a shorter period than it would under natural conditions. Changes to the natural hydrological pattern

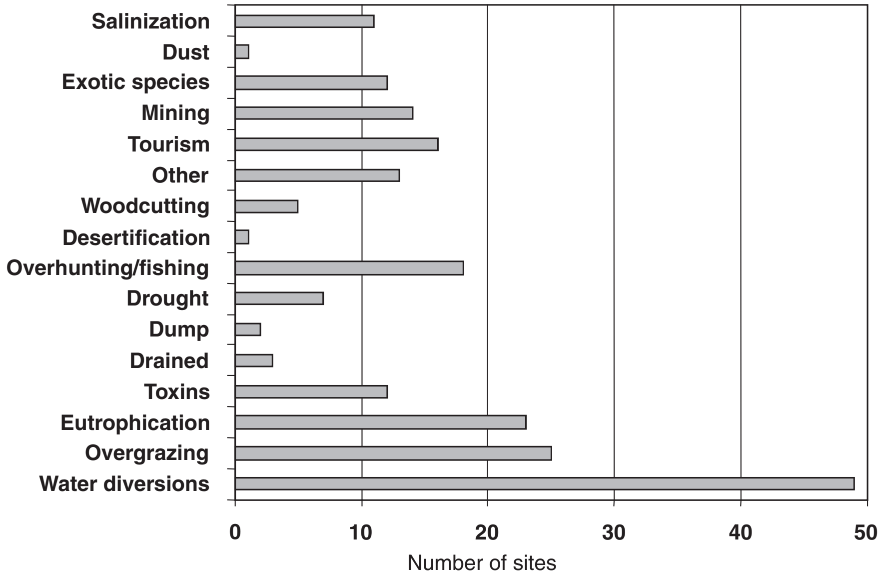

Fig. 7.2. Summary of threats to Ramsar sites including saline lakes (137 total sites), but excluding coastal lagoons. *Source:* Ramsar Site Descriptions (www.ramsar.org.).

have important consequences for seasonal ecological events (Chapters 5 and 6).

In a few cases, urban development on catchments poses a threat to salt lakes. In this context, public opposition has placed on hold the plans for housing developments within the actual crater rims of two volcanic salt lakes, Bullen Merri and Gnotuk, in the Western District of Victoria, Australia. This development threatens the aesthetic and scientific values of both lakes (Timms 1976). Urban development on salt lake catchments has many effects. For salt lakes, the most important impacts may involve localized domestic pollution and loss of aesthetic appeal.

Summary of threats

Overall, the anthropogenic impacts are geographically widespread, mostly irreversible, and degrade values of salt lakes. Certain impacts may be more important on particular sorts of salt lakes, but many are subject to several impacts at the same time. Salt lakes have generally received much less attention and study than freshwater lakes, and it is difficult to derive a representative or summary view of the extent and magnitude of worldwide impacts. The Ramsar Convention on International Wetlands includes all types of inland water bodies within its scope and salt lakes are fairly well represented by 137 sites within the list of 1308 Wetlands of International Importance (Wetlands International 2002). While many salt lakes are subjected to multiple impacts (Fig. 7.2), including most of those common to freshwater lakes (Chapters 5 and 6), water diversions are the predominant threat, affecting 36% of the Ramsar sites. Because the ecological values of salt lakes are not widely recognized and their waters are not used for human consumption, some threats such as pollution may be underreported and only noted following catastrophic fish or bird kills. Only a few salt lakes, those located in arid regions, still remain relatively unimpacted by anthropogenic activities. Furthermore, overall increases in temperature and regional changes in precipitation and runoff (IPCC 2001*d*) will dramatically impact salt lakes.

FRESHWATER CRISIS AND CONSERVATION OF SALT LAKES

The ever-increasing human population in semi-arid regions, with the concomitant expansion of activities to support them, notably drainage, irrigation and land-use changes, will make conservation of salt lakes extremely difficult. An imminent freshwater crisis is widely forecast throughout much of the world as water demand rises, primarily for increased agriculture (Cosgrove & Rijsberman 2000). Worldwide, plans for infrastructure improvements (dams, diversions and irrigation) are being made with little attention to the environmental impacts on salt lakes. Furthermore, even infrastructural improvements are not deemed sufficient to avert water shortages.

Objective analyses of the benefits and costs of salt lake degradation are rarely if ever undertaken. The usual situation is one where the relatively easily determined economic benefits derived from lake degradation, which are often of local value, are judged to outweigh the indeterminate costs of conserving and protecting the lake, which is often of wider value. In water-stressed regions the economic value of water may far outweigh economic values of particular salt lakes, and only an appreciation of non-economic values can tip the balance toward conservation.

Given these factors, there is little doubt the worldwide desiccation of salt lakes will continue. Several recent 'vision' statements clearly point in this direction. In central Asia, for example, the 'vision' proposed by UNESCO (2000) for the Aral Sea basin (*sic*) involves almost complete desiccation of the lake itself, and greatly increased 'development' of its catchment to support the growing populations of Kazakhstan, Uzbekistan and Turkmenistan. Also, state planning in China calls for further increases in irrigated agriculture including many large water projects.

The problem is compounded by the failure of international intergovernmental bodies to recognize properly the importance of salt lakes as integral elements of the world's set of inland aquatic ecosystems. The influential 'World Water Vision' advanced at the Second World Water Forum at The Hague in 2000 did not refer to salt lakes (Cosgrove & Rijsberman 2000), and salt lakes were similarly ignored at the Third World Water Forum. Likewise, Groombridge and Jenkins (1998), in a report to the World Conservation Union (IUCN), did not rate salinization as a significant threat to loss of biodiversity.

It is difficult to be optimistic about the conservation of salt lakes. However, recent progress in recognizing the ecological values of salt lakes and gaining nominal protection has been achieved through the Ramsar Convention and the efforts of its partner organizations (Wetlands International, IUCN, Birdlife International, Worldwide Fund for Nature) and many small non-governmental organizations (NGOs) dedicated to conservation of individual salt lakes. The Ramsar Convention defines wetlands broadly as 'areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres', and thus explicitly includes seasonal, episodic and permanent salt lakes. A number of important salt lakes have been designated as Ramsar sites (Table 7.1) and while the current number is only a small fraction of important salt lakes, more are being listed each year.

The Convention's mission is 'the conservation and wise use of all wetlands through local, regional and national actions and international cooperation, as a contribution towards achieving sustainable development throughout the world'. Among other provisions, contracting parties are obliged to develop national wetland plans. While compliance is largely voluntary, the Ramsar Bureau's unique blend of education, technical assistance and NGO activities has been successful in raising public awareness of wetland values (Bowman 1995, 2003). Because the economic value of freshwater inflows is often considerable, appreciation of the ecological (and non-economic) values of particular salt lakes will often be a necessary prerequisite to establishing legal protection. Thus, the Ramsar Bureau's focus is well suited to the conservation of salt lakes.

Raised awareness is, however, merely the first step. Subsequently, there must be implementation of effective local, national and international management and conservation measures designed to mitigate and minimize the adverse human impacts on salt lakes and, wherever possible, prevent damage to their natural character. Freshwater lakes and wetlands have long been recognized as important natural assets with values over and above their use as a source of water; the need for salt lakes to be similarly recognized is overdue. The inclusion of salt lakes in preparations of a 'World Lake Vision' by several international groups (e.g. the International Lake Environment Committee [ILEC] and Global Water Partnership [GWP]) is essential. Better recognition by the Convention on Biological Diversity and in national wetland strategy documents is also needed. The International Society for Salt Lake Research (ISSLR 2007) should be of value in achieving this recognition.

At the local level, the protection and restoration of Mono Lake provide an outstanding example of what is possible once the total set of values for a salt lake is properly recognized. What factors were important in stopping the diversions? The first and most important was the commitment of a local NGO (Mono Lake Committee 2006) and regional conservation organizations (Audubon

Table 7.1. *Well-known examples of the 137 Ramsar sites that include saline lakes*

Name	Country	Type of saline lakes[a]	Ramsar site size (ha)
Lagunas de Vilama	Argentina	Q, R, Sp, Ss	157 000
Laguna de Llancanelo	Argentina	Q, R	65 000
Banados del Rio Dulce y Laguna de Mar Chiquita	Argentina	Q	996 000
Lake Gore	Australia	R	4017
Western District Lakes	Australia	Q, R	32 898
Laguna Colorado	Bolivia	Q	51 318
Lagos Poopó y Uru Uru	Bolivia	Q	967 607
Quill Lakes	Canada	Q, R, Sp, Ss	63 500
Partie tchadienne du lac Tchad	Chad	Ss, Sp	1 648 168
Niaodao ('Bird Island') in Qhing Hu	China	Q, Sp, Ss	53 600
Sambhar Lake	India	Q	24 000
Lake Urmia	Iran	Q, Sp	483 000
Lake Bogoria	Kenya	Q	10 700
Lake Nakuru	Kenya	Q, Ss	18 800
Issyk-kul	Kyrgyzstan	Q	629 800
Valley of Lakes	Mongolia	Q, Sp	45 600
Karakul Lake	Tajikstan	Q	36 400
Kourgaldzhin and Tengiz Lakes	Kazakhstan	Q	260 500

[a] Lake types: Q, permanent saline/brackish/alkaline lakes; R, seasonal/intermittent saline/brackish/alkaline lakes; Sp, permanent saline/brackish/alkaline marshes/pools; Ss, seasonal/intermittent saline/brackish/alkaline marshes/pools.
Source: Ramsar Sites Database (www.ramsar.org).

and CalTrout). Their intense efforts were maintained over many years, and involved not only developing new legal concepts in environmental law, but also educating the public as to the importance of scenic, recreational and ecological values which were being impacted by water diversions (Hart 1996). The Ramsar Convention is well suited to the work of local NGOs.

Other successful conservation efforts in the Great Basin (USA) include management plans for Abert Lake (Oregon) that maintain salinities within an appropriate range; the use of the Endangered Species Act to halt the desiccation of Pyramid Lake and restore spawning runs of endemic trout (Truckee–Carson–Pyramid Lake Water Rights Settlement Act); and abandonment of mining plans at Zuni Lake (New Mexico) following national attention by the Sierra Club.

However, such successes will most probably be achieved in well-developed affluent countries with numerous conservation organizations; efforts toward conserving salt lakes have mixed results. The extension of the 'Public Trust Doctrine' (Broussard 1983) at Mono Lake to include non-economic values was a landmark environmental case in California, but it is not directly applicable to Walker Lake, which is rapidly being desiccated just 50 km away in Nevada; numerous small salt lakes have in fact been impacted by agriculture throughout the Great Basin.

Given the economic value of fresh water and the current shortage and pending crisis in availability, most large salt lakes are likely to undergo significant desiccation. In some cases, efforts may succeed in conserving part of the ecological value of these lakes. At the Salton Sea, efforts are under way to build a dam across the lake to enable maintenance of moderate salinities in the 35–45 g per litre range in a portion of the lake while letting the other half dry. At the Aral Sea, a World Bank project on the Syr Darya in Kazakhstan has been building a dyke across the Berg Strait, which will maintain the Northern Aral Sea at 15–20 g per litre while the Large (southern) Aral Sea dries. In addition to preserving deltaic wetlands, these salinities will allow the fisheries to be maintained in the Northern Aral Sea. Similar dyking projects are likely to be considered at other large salt lakes in an effort to conserve some ecological values while diverting water for irrigated agriculture. In these and other conservation efforts, scientists will play a key role in assessing ecological impacts and proposing management alternatives.

These current and expanding conservation efforts might be capable of conserving a large portion of ecologically important salt lakes throughout the world if the human population were not increasing and if current agricultural practices were sustainable (Brown 2003). Desertification and salinization are annually removing tens of thousands of hectares from agricultural production. Groundwater depletion is likely to reduce agricultural production across large regions to the 2025 time horizon and possibly much sooner. Coupled with increasing population, these factors almost mandate increased diversions of surface water for irrigated agriculture in all the endorheic basins of the world.

Humans use only *c.*10% of the world's annually renewable water resources and 70% of that is used by irrigated agriculture employing, for the most part, inefficient methods (Cosgrove & Rijsberman 2000). Thus the water crisis might be manageable, given sufficient will and international cooperation. However, this ignores the regional and temporal distribution of water resources, the lack of institutional and water management infrastructure, and regional population demography. By 2025, 1 billion people are expected to experience severe and socially disruptive water shortages (Duda & El-Ashry 2000). Even optimistic forecasts, including improved irrigation, full-cost pricing for water and genetically modified crops that require less water, suggest 20–65% more water will need to be diverted for irrigated agriculture. As we enter a period of severe regional shortages of fresh water throughout much of the world, the economic value of salt lakes, which is mostly for fisheries, is likely to pale in comparison to the value of the fresh water required to reduce or reverse the shortages; current progress of conservation efforts is likely to be stalled or even reversed.

LIKELY STATUS OF SALT LAKES IN 2025

For salt lakes as a whole, the future looks certain: by 2025, most salt lakes will have undergone some changes from their natural character, many permanent ones will have decreased in size and increased in salinity, and many unnatural salt lakes will have appeared either as new water bodies or as replacements for freshwater lakes. How far this process will have gone by 2025 depends on many factors and the extent of change will differ among regions and types of lakes involved (Williams 1996*b*). For purposes of discussion, salt lakes are considered below as permanent, seasonally filled or episodically filled water bodies.

Permanent salt lakes

With the exception of those few permanent salt lakes water levels of which are monitored and managed (for example Mono Lake), and the few in areas where secular decreases in aridity have occurred recently (for example Issyk-kul), by 2025 most permanent salt lakes will have become smaller and more saline, with extensive if not complete exposure of their beds to the atmosphere. This regression will certainly be the fate for almost all permanent salt lakes with defined surface inflows. Large-scale water diversions are being planned in many salt lake basins and the argument that the economic value of diverted water exceeds the sum of all other values attributable to a lake is widely, if uncritically, applied. It is being used to justify diversions from Mar Chiquita (Argentina) despite this lake's critical importance to migrant waterfowl in the western hemisphere (Reati *et al.* 1997). In more optimistic scenarios, management actions will be taken to preserve a portion of the ecological values by maintaining some of the lake at lower salinity than the rest.

Not all permanent salt lakes have well-defined surface inflows of economic value. Trends in their limnological features are less well documented, predictions are hence more uncertain. Some intermittent data, however, are available for several salt lakes in Victoria, Australia, and equally indicate decreasing lake sizes. The reasons for their regressions are not clear, but groundwater pumping, land-use changes in the past century and a secular increase in aridity have been proposed. By 2025, all will have become significantly smaller and some of the shallow lakes that now dry only occasionally will become more or less permanently dry. In Mexico, it is clear that groundwater pumping is eliminating permanent salt lakes. This situation is deemed to be similar elsewhere for permanent salt lakes without defined inflows.

The few permanent salt lakes that show no regression at present are likely to remain the same size by the year 2025, providing no marked climatic changes take place over their catchments. This prediction, however, is less firm than predictions advanced for other permanent salt lakes: recall, for example, how quickly the regression of the Caspian Sea in the 1970s was reversed (Kosarev & Yablonskaya 1994) and the recent rapid rise and now fall of the USA's Great Salt Lake. Other sorts of adverse changes are also likely to occur in some of these lakes. The coelenterate and ctenophore introductions into the Caspian Sea are likely to change the nature of this lake's food web in the next two decades, overfishing will continue to be a problem and further adverse changes are likely from oil pollution.

Seasonally filled salt lakes

For seasonally filled salt lakes, in other words most natural temporary salt lakes in semi-arid regions, data on recent trends in hydrological periodicity are few, although many of these lakes are known to have dried more or less permanently following land-use changes, which will continue. Probably, the trends will reflect those shown by permanent salt lakes in the same region; the lakes will be drier for longer periods by 2025, some permanently so.

This simple picture of increasing desiccation is complicated by two events that are already common and are of increasing importance in semi-arid regions, namely salinization and the disturbance of salt and water budgets within drainage basins by diversion of river water. Land-use changes and irrigation, which are expected to increase globally by 50–100% by 2025 (Gleick 1993*b*), are implicated in both events.

Salinization has already increased the number of salt-water bodies in semi-arid regions and will continue to do so up to and beyond 2025. It has also enlarged natural salt lakes. The effects of water diversions from rivers are likely to be similar, though taking longer to develop; essentially, the diversions redistribute the salt and water load before its discharge to an inland terminus (a salt lake) or the sea. Both endorheic and exorheic drainage basins are involved (W. D. Williams 2001). The catchment itself, therefore, serves as the 'sink' for salts leached from it and so accumulates them. It is noted that salts within the Syr and Amu Darya are now retained within the catchment of the Aral Sea and not discharged into the lake. Similar salt retention within catchments can be assumed wherever significant diversions from rivers in semi-arid regions are made, as in the Murray–Darling River (Australia), the Yellow River (China) and the Colorado River (USA), all of which now have greatly reduced final discharge rates.

Episodically filled salt lakes

Episodically filled salt lakes, most temporary salt lakes in arid regions, are at present the type of salt lake least impacted by human activities, and in absence of global climate change most may retain their relatively natural status to 2025. However, several climate models predict that warming will be particularly great and rapid in certain arid regions (IPCC 2001*d*), and recent extended droughts in Australia may already reflect this (Karoly *et al.* 2003). Other arid regions will be less impacted, or will be affected more slowly. Current models predict that Australia will be warmer and drier throughout much of the interior and that large regional changes in runoff and precipitation will occur throughout the Middle East and central Asia. However, considerable differences exist between models concerning regional predictions of precipitation and runoff (Chapter 1). Irrespective of what happens, even small climate changes by the year 2025 could markedly influence the natural status of episodically filled salt lakes. The possible impact of climate change on the periodicity and intensity of El Niño–Southern Oscillation (ENSO) phenomena may be particularly important. ENSO episodes presently have considerable impact on precipitation patterns in many arid regions in North and South America, Africa and Australia (IPCC 2001*d*).

CONCLUSIONS

Salt lakes are geographically widespread, numerous and a significant part of the world's inland aquatic ecosystems. They are important natural assets with considerable aesthetic, cultural, economic, recreational, scientific, conservation and ecological values. Some features, notably the composition of the biota, uniquely distinguish them from other aquatic ecosystems. Salt lakes develop as the termini of inland drainage basins where hydrological inputs and outputs are balanced. These conditions occur in arid and semi-arid regions (approximately one-third of the total world land area). Many human activities threaten or have already impacted salt lakes, especially surface inflow diversions, salinization and other catchment activities, mining, pollution, biological introduction, and anthropogenically induced climatic and atmospheric changes. By 2025, most natural salt lakes will have undergone some adverse change. Many permanent ones will have decreased in size and increased in salinity, and many unnatural salt-water bodies will have appeared. In certain regions, many seasonally filled salt lakes are likely to be drier for longer periods. The extent to which episodically filled salt lakes will change by 2025 will largely depend upon the nature of climate change in arid regions. Objective cost–benefit analyses of adversely affected salt lakes are rare, and international bodies have not yet recognized salt lakes as important inland aquatic ecosystems. To redress this situation, there is a need to raise awareness of: the values of salt lakes, the nature of human threats and impacts on them, and their special management requirements. More effective management and conservation measures need to be developed and implemented. The conservation of salt lakes will be made much more difficult by the impending freshwater crisis, which will be experienced by many countries in arid and semi-arid regions of the world, and by the anticipated increases in irrigated agriculture. Ultimately, the fate of many permanent salt lakes will depend on how quickly individual countries move towards improved and sustainable agricultural practices and stabilization of their human populations.