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Environmental threats to salt lakes and the likely status of inland saline ecosystems in 2025

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SUMMARY

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. The paper reviews the nature of environmental impacts and their effects upon salt lakes. Its aims are two-fold: to draw attention to the extensive damage that salt lakes have now undergone, and to indicate the likely status of salt lakes in 2025. 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 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 disturbances (e.g. introduction of exotic species), and anthropogenically-induced climatic and atmospheric changes. The effects of such activities are always adverse and include changes to the natural character of salt lakes, loss of biodiversity and fundamental limnological changes. The effects are geographically widespread, mostly irreversible, and degrade the values of salt lakes. Four salt lakes are discussed, namely the Aral Sea in central Asia, Mono Lake in California, USA, and Lake Eyre and Lake Cantara South, in Australia. 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 saline 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 affecting salt lakes are rare, and international bodies have not properly recognized salt lakes as important inland aquatic ecosystems. To redress this situation, there is a need to raise awareness of: (1) the values of salt lakes, (2) the nature of threats and impacts from human activities, and (3) their special management requirements. More effective management and conservation measures need to be implemented. Mono Lake provides an example of what can be achieved in the conservation of salt lakes. Its conservation was largely brought about by (1) the commitment of a non-governmental organization which recognized its non-economic values, (2) the freedom to express views, (3) a legal system which took account of non-economic values, and (4) a legislature which implemented judicial findings. The conservation of Mono Lake was difficult; the conservation of other salt lakes is likely to be even more difficult. Only international pressure from appropriate organizations will be effective for the conservation of many.

Keywords: saline lakes, salinity, environmental threats, salinization, climate change, conservation

INTRODUCTION

Two sorts of salt water are found on the earth's surface, namely marine waters (the ocean) and epicontinental (inland surface) salt lakes. This paper concerns the latter sort, that is, permanent or temporary bodies of water with salinities >3 g l^{-1} and lacking any connection to the marine environment (i.e. athalassohaline *sensu* Bayly 1967). For the most part, salt lakes are confined to dry regions of the world where evaporation exceeds precipitation and where they are often more abundant than fresh waters (Fig. 1).

Despite the global extent of dry regions (about one-third of total land area) and the number of salt lakes within them, limnologists and other groups interested in inland waters have largely ignored salt lakes until recently, perhaps partly because of misapprehensions about their distribution, global volume and values, all of which have been underestimated. These misapprehensions should be laid to rest promptly before proceeding further.

First, note that salt lakes occur widely in cold and warm/hot dry regions on all continents (including Antarctica). Often they are the dominant landscape features. Second, inland saline waters are not greatly less in total global

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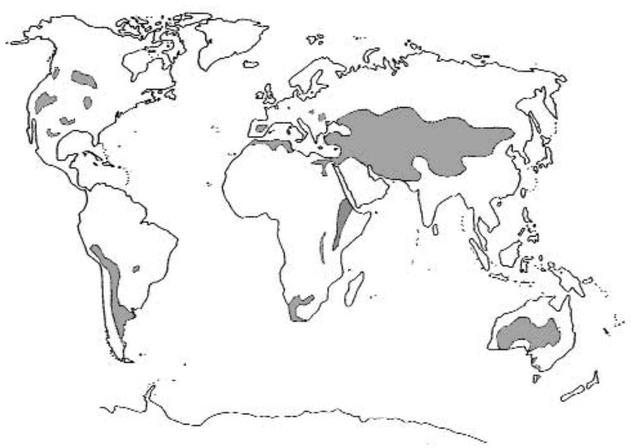

Figure 1 Shaded areas indicate the distribution of salt lakes around the world.

volume than freshwater lakes. The global volume of freshwater lakes is estimated to be 105×10^3 km^3 and of inland saline water to be 85×10^3 km^3 (Shiklomanov 1990). Salt lakes include the largest lake on earth, the Caspian Sea, with an area of 622 000 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*a*). Third, salt lakes have important aesthetic, cultural, economic, recreational, scientific, conservation and ecological values (Williams 1993*a*, 1998*a*). None of these values should be underestimated, though to a considerable degree non-economic values have only recently been properly recognized (Collins 1977). The importance of scientific values, for example, has only become fully appreciated in the past few decades. Often, a particular value is recognized retrospectively, that is, after a particular salt lake has undergone environmental degradation (Williams & Aladin 1991). A case in point, and one explored later in detail, is the Aral Sea. Its ecological values only became clear when it had significantly shrunk in size and increased in salinity following anthropogenic disturbance.

Salt lakes include a variety of aquatic ecosystems. The Caspian Sea, Mono Lake and the Dead Sea, for example, never dry out, although their water levels may fluctuate considerably over long periods (secular fluctuations). In arid regions, many salt lakes, like Lake Eyre in Australia, are filled with water only episodically; for many years, they are simply dry salt-pans and only contain water unpredictably after episodic rain in sufficient amounts has fallen on their catchments. In less arid (semi-arid) regions, where rainfall is predictable each year, many salt lakes, such as in Spain, south-western USA, southern Africa and Australia, lack surface water in the dry season but are filled annually during the wet season.

Differences in hydrological patterns are closely reflected usually by long term or seasonal changes in salinity. Thus, large permanent salt lakes have salinities that, though widely different between individual salt lakes, may vary naturally rather little over long periods. The Caspian, for example, has a more or less constant salinity of about 12 g l^{-1}, and the Aral and Dead Seas, prior to anthropogenically-induced changes, had more or less constant salinities over many decades of approximately 10 g l^{-1} and 200 g l^{-1}, respectively (Aladin & Plotnikov 1993; Williams 1993*b*). Large, episodically-filled salt lakes, on the other hand, have salinities which may vary from <50 to >300 g l^{-1} as they become dry over a period of several months to years after filling (Williams & Kokkinn 1988). Small, seasonally-filled salt lakes may have salinities equally variable, though with fluctuations confined to an annual cycle.

The major ions in salt lakes are the same as those in fresh waters, namely Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-} and CO_3^{2-}/HCO_3^-, but the ionic proportions are different (Hammer 1986). In fresh waters, the divalent cations and HCO_3^-/CO_3^{2-} are important; in salt lakes, Na^+ and Cl^- are usually the dominant ions, though a dominance of Mg^{2+}, Ca^{2+} and SO_4^{2-} is also found in some lakes (Eugster & Hardie 1978).

The differences in salinity (and to some extent ionic composition) between salt lakes and fresh waters are in turn reflected by differences in the composition and nature of the biota. The biota of moderately saline lakes (< about 10 g l^{-1}) mostly comprises halotolerant taxa of fresh waters, but with increasing salinity these disappear and are replaced with taxa found only in salt lakes (Hammer 1986). In all salt lakes, permanent or temporary, adaptations to osmotic stress are needed. In temporary salt lakes, taxa must also have adaptations to survive desiccation. Generally, with increasing salinity, biodiversity decreases, though the pattern of decrease is by no means regular (Williams 1998*b*). Considerable faunal endemicity occurs, and previously held views about the cosmopolitanism of salt lake animals in particular are invalid. Even *Artemia*, once thought to comprise a single worldwide species and referred to as *A. salina*, is now known to comprise many species, some with relatively restricted distributions (Browne & Bowen 1991). Regional endemicity may occur in the fauna of seasonally filled salt lakes.

Thus, the biota of salt lakes with a salinity in excess of about 10 g l^{-1} uniquely distinguishes these aquatic ecosystems from all other aquatic ecosystems. This feature, however, is only one of several unique features of salt lakes. Others include:

- The occurrence of some elements of the biota which are extremely ancient in an evolutionary sense (stromatolites, known to have lived 3000 million years ago; Walter *et al.* 1980) or have unique physiological and biochemical mechanisms for life in salt lakes (e.g. some Archaeobacteria possess a retinal-based pigment, rhodopsin, to capture light energy in a process markedly different from the photosynthetic process of most plants and algae; Oren 1999).

- Sensitivity to climate change not displayed by other ecosystems. Even small changes in any element of the hydrological budget are reflected rapidly and directly by physico-chemical and biological events. This feature is of considerable use to palaeoclimatologists who can make inferences about past climates from the analysis of salt lake sediments (e.g. Zeeb & Smol 1995).
- The high degree to which salt lakes are discrete ecosystems. Salt lakes, by definition, are more or less closed hydrological systems and thus offer unique opportunities for the study of ecosystem attributes within clearly defined physical limits. Their decreased biodiversity and reduced habitat heterogeneity contribute to the ease of such studies.
- The complexity of geological, hydrological and geochemical interactions. This feature offers considerable opportunities for the study of oceanic and continental evolution.

This paper reviews the nature of environmental impacts and their effects upon salt lakes. While most of these have long been recognized as important for individual salt lakes, their global extent, rapidity and common trend in degrading a significant and unique component of the biosphere have not been fully appreciated. One objective of the review is to draw attention to this situation. A second objective is to indicate the likely status of inland salt lakes by the year 2025, given the nature of current impacts and effects on salt lakes. Only clear recognition of the extensive damage that salt lakes are now undergoing, and the likely result that such damage will lead to within the next 25 years, offers any hope that present trends can be changed.

THE DEVELOPMENT OF SALT LAKES AND THE IMPORTANCE OF CLIMATE

The type and nature of human activities affecting salt lakes are considered further below, but, to understand why most are so important, a brief explanation of the basic principles underpinning the existence of salt lakes is needed. Another reason for providing this explanation is that environmental impacts on salt lakes are often exacerbated by a lack of understanding of basic hydrological, geochemical and ecological differences between saline and freshwater lakes (upon which most knowledge about lake processes is based). Consequently, ill-informed management practices frequently prevail.

The development of salt lakes

Two basic conditions must be met for salt lakes to develop. The lake must be the terminus of a closed (endorheic) drainage system, and there must be a balance between hydrological inputs (surface and subsurface inflows and precipitation over the lake) and outputs (evaporation and seepage to sediments). This balance must be such as to allow the permanent or temporary persistence of a body of water. These conditions most often occur in arid and semi-arid regions. Figure 2 illustrates the general relationship between solute concentrations in lake waters (as compared to inflow concentrations) and the balance between evaporation and precipitation. It is assumed that no solutes are lost through seepage. This balance, f_1, is given by the equation:

$$f_1 = \frac{[(v)_{evap} - (v)_{prec}]}{(v)_{infll}}$$

where $(v)_{evap}$ = the average volume of water lost by evaporation, $(v)_{prec}$ = the average volume of water gained from precipitation, and $(v)_{infll}$= the average volume of water flowing into the lake. Clearly, the greater the net evaporation, the more concentrated do lake solutes become. Note that the relationship is hyperbolic (Fig. 2).

The importance of climate

The three most important climatic factors determining the development of salt lakes are temperature, net evaporation and precipitation (Fig. 3). Salt lakes can occur within regions where mean annual temperature can vary from 0 °C to >30°C and mean annual precipitation from 50 cm to >100 cm, but become progressively more episodic (ephemeral) with increasing annual evaporation (0 cm to >200 cm). Figure 3 also shows the position of seven important salt lakes (or salt lake regions) with regard to these factors.

Because the existence of salt lakes involves a balance between several climatic factors, long-term, secular changes in climate have considerable impact on salt lakes. Many palaeolimnological studies of salt lakes clearly demonstrate past regressions and transgressions in lake volume (and hence past changes in salinity and ecology; Bowler 1981). Even lakes that have had quasi-stable conditions for many decades are known to have been unstable in previous periods. The Aral Sea is a case in point; between 1910 and 1960, its morphometry, salinity and ecology were relatively stable, but before the 20th century, many transgressions and regressions had occurred (Letolle & Mainguet 1993).

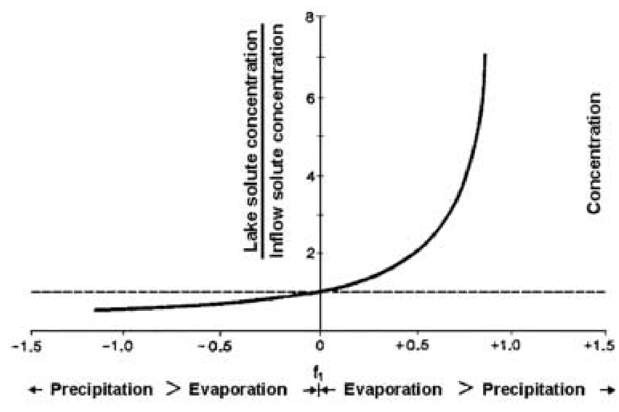

Figure 2 The relationship between lake salinity and inflow salinity, and the balance between evaporation and precipitation. After Carmouze and Pedro (1977).

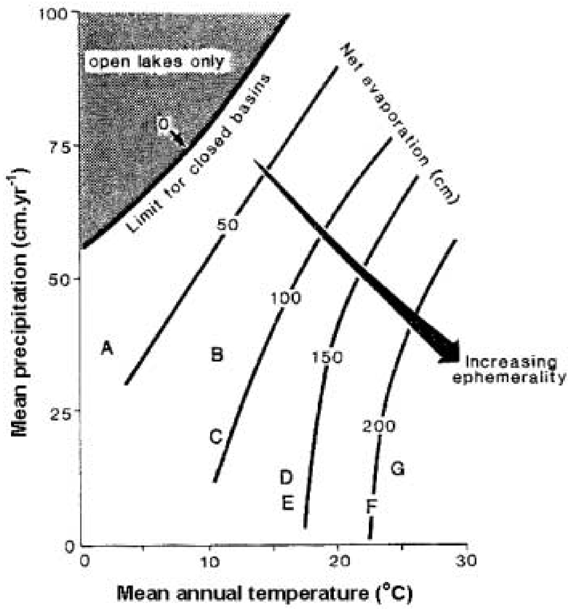

Figure 3 The effects of temperature, net evaporation and precipitation in determining the development of salt lakes. Also shown are the occurrence of certain closed lakes in relation to climate. A = saline lakes of Saskatchewan; B = Great Salt Lake, Utah; C = Mono Lake, California; D = Salton Sea, California; E = Owens 'Lake', California; F = Dead Sea, Israel/Jordan; G = Lake Eyre, Australia. Modified after Langbein (1961) and Cole (1968).

Climatic changes over shorter periods also exert considerable impact. Notable here is the globally important circulation pattern involving the ocean and the atmosphere, the El Niño-Southern Oscillation (ENSO). The climate of many arid and semi-arid regions is linked to the intensity and periodicity of El Niño episodes (and its opposite phenomenon, La Niña; IPCC [Intergovernmental Panel on Climate Change] 1996). ENSO is related to variations in sea-surface temperatures and air pressure in tropical and subtropical parts of the Pacific Ocean (IPCC 1996). During an El Niño episode, the tropical eastern part of the Pacific has higher surface temperatures and lower air pressure, with the reverse applying in the tropical western part. During La Niña episodes, the opposite situation prevails. Both episodes affect precipitation in many arid and semi-arid regions. Thus, in El Niño episodes, arid and semi-arid regions in the mid-latitudes of western North and South America receive increased rain, whereas Australian arid and semi-arid regions receive less. The opposite applies during La Niña episodes. Any change to the length, intensity and frequency of ENSO phenomena will clearly have profound effects upon the climates of arid and semi-arid regions and hence the nature of salt lakes within them.

ENVIRONMENTAL IMPACTS AND EFFECTS

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

Overall, then, human activities that pose a heightened or significant threat to salt lakes, or which have already had a significant impact are: surface inflow diversions, salinization and other catchment activities, mining, pollution, biological disturbances, and anthropogenically-induced climatic and atmospheric changes. Their relative importance varies according to the type of lake involved and time.

Their effects are usually adverse as far as they involve changes to the natural character, loss of biodiversity, and fundamental limnological changes. Overall, the effects are geographically widespread, mostly irreversible, and result in the degradation of values attributed to salt lakes. Certain impacts and their effects may be more important to particular sorts of salt lake but, many salt lakes are subject to several impacts at the same time. Only a few salt lakes, those located in arid regions, still remain relatively unimpacted by anthropogenic activities.

To provide substance to these general points, the nature of environmental impacts and their effects on salt lakes are considered separately below. Note that it is often difficult directly to associate some effects, such as biodiversity loss, with a particular impact. Some impacts have much the same effects, for example surface flow diversions and salinization.

Surface inflow diversions

The most important activity impacting large permanent salt lakes is the diversion of freshwater inflows from them to provide for agricultural and other human needs. Since diversions alter the hydrological budget (see above), and salt lakes respond quickly to such alterations, inflow diversions invariably cause a rapid decrease in lake volume and the several physical and chemical features contingent upon volume, especially water level and salinity (Williams 1993*a*).

Inflow diversions have been greatest and had the most profound effects in the Aral Sea. Prior to 1960, the annual volume of inflows from the Syr and Amu Darya was 56 km^3; after diversions, the annual average inflows in the decades that followed were 43.3 km^3 (1961–1970), 16.7 km^3 (1971–1980), and 4.2 km^3 (1981–1990) (Letolle & Mainguet 1993). The water level of the Aral Sea has fallen >15 m since 1960. The massive diversions of water were used to irrigate crops, particularly cotton and rice.

Other examples are Mono Lake, USA, where water levels have fallen 15 m since 1920; Pyramid Lake, Nevada, USA, where water levels have fallen by about 21 m since 1910; the Dead Sea, Israel/Jordan, where water levels have dropped 8 m since 1980; Qinghai Hu, China, where water levels have dropped about 10 m since 1908; and Lake Corangamite, Australia, where levels have dropped 3 m since the 1960s (Williams 1993*b*). Only a few permanent salt lakes in the recent past have maintained or increased water levels, despite flow diversions in some cases, a fact generally attributable to increased inflows following secular increases in regional precipitation. The most notable examples are the Great Salt Lake (Utah, USA), the Caspian Sea (Russia and Iran), and Mar Chiquita (Argentina). With regard to salinities within the times indicated, in the Aral Sea salinity has increased from 10 to >50 g l^{-1} , in Mono Lake from 48 to about 90 g l^{-1}, in Pyramid Lake from 3.75 to >5.5 g l^{-1}, in the Dead Sea from 200 to 340 g l^{-1}, in Qinghai Hu from 5.6 to 12 g l^{-1}, and in Lake Corangamite from 35 to around 50 g l^{-1} (Williams 1993*b*).

The biological effects of increased salinities depend largely upon the original salinity. They are greatest when the original salinity is low, and least when it is hypersaline. Thus, the effects of the 20 g l^{-1} increase in Lake Corangamite was significant and led to the almost complete disappearance of fish, amphipods, snails and *Ruppia,* with consequent effects on the associated avifauna that fed on the lake (Williams 1995). Conversely, the >100 g l^{-1} increase in the Dead Sea had little effect on the biota of this lake and fundamental processes within it (Williams 1993*b*).

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

Ultimately, inflow diversions can lead to the complete loss of the lake, as in Winnemucca Lake in Nevada and Owens Lake in California. 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 l^{-1} in 1884 (Clarke 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 l^{-1} (Clarke 1920). From 1913, diversions of water from the lake to provide domestic supplies to Los Angeles led to its complete desiccation by 1924. It is now a large salty and dusty plain. One known effect of the drying of Owens Lake is that its bed now gives rise to significant emissions of small dust particles that add to the smog load of the Owens Valley. The bed also has high levels of phytotoxins including arsenic and boron. Control of dust emissions is being attempted by planting salt tolerant grasses, which require irrigation.

Salinization

While one of the effects of surface inflow diversion from large salt lakes is, inevitably, an increase in the salinity of the lakes, other activities often bringing about salinity increases in salt lakes include clearance of the natural vegetation and other land-use changes within catchments (Williams 2002). The process of salinization involves the mobilization of salts dissolved in underground water; the salts move towards the surface as the water-table rises following a decrease in the amount of underground water transpired by deep-rooted plants (or following the addition to groundwater of excess irrigation water), and once near the surface, capillary action brings them to the surface (Williams 2002). 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; freshwater lakes and other inland bodies of fresh water are affected too, and secondary salinization is a major threat to water resources in semi-arid and arid regions of the world (Williams 1999, 2001, 2002).

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 an estimate of some 10 million km^2 of land has been advanced as the global area already affected (Gleick 1993). What is certain is that salinization has disturbed the natural hydrological and salt cycles in many dry land 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 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 consequential effects of these. Direct physical effects are less because, unlike flow diversions, secondary salinization is not associated with large changes to 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, because secondary salinization affects fresh as well as saline water-bodies, one of its effects has been to increase the number of saline waters. Another is to alter natural hydrological patterns.

Overall, the major effects of secondary salinization may be summarized as:

- a change in the natural character of many water bodies in semi-arid regions, frequently including changes to natural hydrological patterns;
- a replacement of a less halotolerant biota by a more halotolerant one; and
- a decrease in biodiversity.

Other catchment activities

Soil erosion, increased sediment loads and changes in run-off 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, run-off 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 have important consequences for seasonal ecological events.

Groundwater pumping for agricultural purposes threatens many shallow salt lakes that are essentially surface 'windows' of shallow water-tables (Williams 1993*a*). Already, most of the *axalpazcos* (shallow, temporary salt lakes) in central Mexico have disappeared because of over-pumping of underground water for irrigation (Alcocer & Escobar 1990), and many temporary salt lakes in central Spain are similarly threatened or affected. The natural character of the latter are also affected (though in a different way) by another catchment activity, namely the planting of irrigated crops, especially vines, close to lake margins. Frequently, pumping may be taking place many kilometres from affected lakes.

In a few cases, urban development on catchments poses a threat to salt lakes. In this context, attention is drawn to plans for the development of housing actually within the crater rims of two volcanic salt lakes, Bullen Merri and Gnotuk, in the Western District of Victoria, Australia. Both lakes have many values threatened by this development, particularly aesthetic and scientific values (Timms 1976). Urban development on salt lake catchments has many effects, as indeed it does on all lake catchments. For salt lakes, the most important ones are likely to involve localized domestic pollution and a loss of aesthetic appeal. Finally, the planting of irrigated crops close to salt lakes usually means that excess irrigation water enters the lake directly, so increasing lake volume and thereby reducing natural salinity. Changes to natural hydrological patterns are also involved.

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 evaporates, 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 caused by mining, 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).

In passing, it may be noted that mining can also lead to the development of unnatural saline water-bodies in temperate regions. The moderately saline lakes or 'flashes' in Cheshire, UK, are the result of land collapses over saline deposits mined from underground. Quarries containing saline water in Germany developed when the pumping of saline 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 saline groundwater) provides a unique example of unnatural saline water-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 the use of dry salt lake beds as racetracks.

The limnological effects of physical disturbance to dry salt lake beds 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 not known. They may not be significant. In this context, note that the biota of salt lakes, especially episodically-filled ones, 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 the impacts on the appearance of 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 the aesthetic appeal of dry salt lake beds and destroy a core part of their 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). Saline wastewater will have less profound effects, but will at least alter the natural pattern of salt loading. Hydrocarbons released accidentally by mining for oil in the Caspian are already having an injurious effect on the economically important sturgeon in the lake (Kosarev & Yablonskaya 1994).

Of actions other than mining which 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 landfilling have all but obliterated the original lake.

Pollution

Pollution also occurs through inputs of agricultural wastewater (often saline), pesticides in run-off and a variety of organic and inorganic wastes from domestic and industrial sources. Plant nutrients, the major cause of eutrophication in freshwater lakes, appear not to be major pollutants in salt lakes, though exceptions occur (Williams 1981). Because salt lakes are usually regarded as water bodies of little value, they are often used as sites for dumping solid wastes also.

The effects of pollution are broadly the same on salt lakes as on freshwater ones (Williams 1993*a*). Moreover, all of the sorts of pollutants discharged into fresh waters are also discharged into saline 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). Many pollutants in the Caspian Sea come from the Volga (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. Often, the same discharge criteria are used by environmental protection agencies for both saline and freshwater lakes (Williams 1981). This takes no account of the fundamental hydrological differences between fresh and saline lakes. The point stressed in this context is that salt lakes are more or less closed hydrological systems and so accumulate and biomagnify many pollutants to a much greater degree than the open hydrological systems of 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 (artificial salt lakes constructed to manage saline wastewaters) in the western part of the USA provides an example (Schroeder *et al.* 1988). Selenium was soon transmitted to waterbirds that used the ponds; primary effects were mortality and deformity of adult birds (Schroeder *et al.* 1988).

Biological disturbances

The biota of many salt lakes has been unnaturally disturbed by the introduction of exotic species. All types of salt lake are threatened or have been affected in this way. Fish of recreational interest have been introduced into many moderately saline lakes; often these are species that cannot breed *in situ* and populations are maintained by continual restocking. Several lakes in Canada and Bolivia, and at least one Australian lake (Lake Bullen Merri, salinity about 8 g l^{-1}) provide examples (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 rises in salinity in this lake. In the Caspian Sea, likewise, many fish introductions were made; at least nine of these species are still present in the lake (Kosarev & Yablonskaya 1994).

Many invertebrate introductions to moderately saline permanent lakes have also taken place. Thus, of 18 invertebrate species introduced into the Aral Sea, either accidentally or deliberately from 1927 onwards, and 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 rose beyond their halotolerance. In the Caspian, 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 recent ones, the coelenterate *Aurelia aurita* and the ctenophore *Mnemiopsis leidyi*, considered highly likely to have significant impacts on some fish populations (N.V. Aladin, personal communication November 2001).

Temporary and/or highly saline 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*, a brineshrimp, into coastal solar salt-pans to decrease 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). There are now reports that a species of *Artemia* from coastal salt-pans in Western Australia has recently invaded inland natural salt lakes (B. Knott, personal communication July 2000).

Other forms of biological disturbance apart from exotic introductions exist; for example, predation by terrestrial predators of bird species dependent on salt lakes for breeding and food is important. Thus, the existence of some species of flamingo in South America is threatened by human removal of eggs (Hurlbert & Flores 1988). As the Aral Sea shrank following inflow diversions, many small islands in the southeast of the lake became peninsulas, so allowing predators access to populations of migratory and resident waterfowl populations (Williams & Aladin 1991). And 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 (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 subsequent investigations, when they occur, are more concerned to determine to what extent introduced species have acclimatized than with any adverse impacts on native species. Nevertheless, there is some evidence that introduced species which become acclimatized do compete with and 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* brineshrimp species, at least in the highly saline ponds (Mitchell & Geddes 1977). This has serious implications for *Parartemia* in natural salt lakes. The spread of *Artemia* into natural salt lakes in Western Australia has already been noted.

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 then decrease in abundance (N.V. Aladin, personal communication November 2001).

Additional predation on waterbirds associated with salt lakes is likely to lead to decreased populations of the bird species involved and in some cases to extinction. Thus, in Australia, since the banded stilt breeds only at the margins of episodically filled salt lakes, its existence is probably already finely balanced; significant additional predation pressure from silver gulls could well bring about extinction (Robinson & Minton 1990).

Climatic and atmospheric changes

Because salt lakes are particularly sensitive even to small changes in any component of their hydrological budgets, small changes in climatic variables, especially evaporation and precipitation, quickly affect them. Global climate warming, therefore, transmitted mainly through increased cloud cover and changes to the amount and timing of precipitation and evaporation, will affect salt lakes more so than freshwater lakes and other inland waters. The effects will be compounded by the fact that salt lakes occur mainly in semi-arid regions where most climatic models predict the greatest increases in temperature will occur (Hammer 1990; IPCC 1996). In the Aral Sea region, for example, temperature rises of up to 6°C are forecast for the present century.

The effects of climate change will vary regionally according to the nature and extent of the change involved. In the very broadest of terms, lakes will change as aridity increases or falls according to the following pattern (see also Fig. 3):

Climate:	arid	↔	semi-arid	↔	temperate
Lake:	episodic, saline	↔	seasonal, saline	↔	freshwater
Drainage:	endorheic	↔	endorheic	↔	exorheic

In this pattern, as climate changes, so too does the type of lake and drainage system characteristic for the climate in question. Many climate models predict increasing aridity for several regions that are already arid or semi-arid, such as in central Asia. If this happens, temporary salt lakes in these regions will remain drier for longer, and permanent salt lakes will become smaller and more saline. In situations where temporary salt lakes remain drier for longer, the biota will increasingly include species with good dispersal abilities and the ability to 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 biodiversity in line with the general inverse correlation in salt lakes between salinity and biodiversity (Hammer 1986).

Potentially, atmospheric changes most injurious to salt lakes involve the decrease in the concentration of ozone in the upper strata of the atmosphere (Williams 1998*a*). This decrease is significant because increased penetration of ultraviolet radiation, known to affect biota adversely if excessive, follows. 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 such lake likely to be affected in this way.

CASE STUDIES

To illustrate the nature of the impacts and their effects on particular salt lakes, the Aral Sea (central Asia), Mono Lake (USA), Lake Eyre (Australia), and Lake Cantara South (Australia), have been selected as case studies because they provide examples of the variety of saline ecosystems subject to particular threats or are particularly good or well-known illustrations of certain points. The first two lakes are permanent; the last two are temporary, with Lake Eyre filled episodically and Lake Cantara South filled annually. Frequent reference to these lakes has already been made here. Special attention is directed to the Aral Sea since this lake in particular has been affected by a multiplicity of impacts whose effects have been severe and obvious and which have led to marked degradation in many values of the lake and given rise to many problems.

Aral Sea

The Aral Sea is a large permanent salt lake in semi-arid Uzbekistan and Kazahkstan. Formerly it was the fourth largest lake in the world but after significant diversions of its two major inflow rivers, the Amu and Syr Darya, beginning 1960, it rapidly decreased in size. Prior to 1960, its salinity was about 10 g l^{-1} and Na^+ and Cl^- dominated the major ions. Although its biodiversity, production and endemicity were low prior to 1960, the lake sustained an important commercial fishery yield of 44 000 tonne per annum (Aladin *et al.* 1998). Apart from this economic value, the lake was of value in a cultural sense and as a means of local transport. It also moderated the continental climate of the region, was a sink for salts leached from its catchment, and had high conservation significance, particularly for migratory waterfowl in central Asia (Williams & Aladin 1991). Many features of the lake's history, geology and limnology are described by Letolle and Mainguet (1993).

The diversions of the main inflows from the lake after 1960 caused the lake to shrink rapidly. From an area of about 68 000 km^2 and a maximum depth of 69 m in 1960, it had decreased in area by over two-thirds to less than 20 000 km^2 and a maximum depth of 52 m by 2000 and had divided into a larger, southern lake and a smaller, northern one. The larger lake had decreased to less than a third of its original volume. By 2000, its water level had fallen >20 m, so that all but the largest islands had become incorporated into the contiguous land mass, all coastal embayments lost, and extensive areas of the lake bed were exposed (Letolle & Mainguet 1993). Reflecting these physical changes, the chemistry of the lake also changed, most notably its salinity. This rose to >50 $g\ l^{-1}$ by 2000 (N.V. Aladin, personal communication November 2001). This salinization had little impact at first, but with progressive increases in salinity, major changes to the biota and ecological processes within the lake took place (Aladin *et al.* 1998). These overshadowed whatever changes were a result of the many introductions of exotic species.

One of the most notable changes induced by the increase in salinity was a great decrease in biodiversity. For example, of the almost 200 species of free-living macroinvertebrates and 20 fish species present in the lake before 1960, less than 30 macroinvertebrate species and only 5 fish species had survived by the 1990s (Aladin *et al.* 1998), when salinities began to exceed 30 $g\ l^{-1}$. Even fewer species now occur because of the further increase in salinity, though present knowledge is constrained because of the dearth of recent scientific investigations. Plant diversity also decreased as did primary production. Amongst the first plants to disappear were emergent species in coastal reed communities (Letolle & Mainguet 1993).

These changes in turn led to other changes and had a number of significant consequences for human communities associated with the lake. Of direct economic importance was the collapse of the fishery, a source of both protein and work for local people (Letolle & Mainguet 1993). The loss of the reed beds and coastal islands led to the demise of resident and migratory populations of waterfowl (Williams & Aladin 1991). The exposed lake bed became the source of additional windblown salt and dust. The smaller volume of water in the lake reduced the lake's capacity to moderate the local climate, and, of course, precluded its use as a local transport route. These and other changes to the natural character of the lake affected local human health, which was also affected by increased aquatic concentrations of pesticides, lack of good-quality drinking water, reduced pastoral production and, perhaps, the loss of a culturally significant part of their natural environment. Thus, overall, human impacts on the Aral Sea have led to severe degradation, particularly in economic, cultural, conservational and ecological values.

Since significant volumes of water and their salt loads are no longer discharged into the lake, the lake has ceased to act as the chemical as well as the hydrological terminus for its drainage basin. The salt in the Amu and Syr Darya, therefore, is largely retained within the drainage catchment so adding to the agricultural salt load and the load carried atmospherically from exposed sediments of the lake bed. In other words, one effect of inflow diversion is that the lake no longer acts as the salt sink for the catchment. This retention of salt on the catchment will slightly offset the salinity increase in the lake.

Mono Lake

Mono Lake (California, USA) is another large permanent salt lake. Prior to anthropogenic diversion of its inflow waters (beginning about 1940), its area was >200 km^2 and its maximum depth was 57 m. Its salinity was then about 50 $g\ l^{-1}$, mostly comprising Na^+, Cl^- and HCO_3^+/CO_3^{2-} ions (Patten *et al.* 1987). Biodiversity was and is low, but combines with high biological production (Jellison & Melack 1993). An important element of the fauna is *Artemia monica*, an endemic brineshrimp (Dana *et al.* 1993). Important values of the lake are cultural (to the local indigenous Americans), aesthetic, recreational, scientific (Stine 1990), and conservational (it is an important refuge and feeding area for several migratory waterfowl; Patten *et al.* 1987).

The diversion of surface inflows from Mono Lake is the only significant human impact on this lake. Diversions began in 1941 and were instigated by the Los Angeles water authorities to provide for additional domestic supplies, and resulted in sharp decreases in the volume of the lake and falls in its water level. The latter fell 14 m, from 1956 m above sea level in 1941 to 1942 m in 1980 (Patten *et al.* 1987). In turn, salinity doubled over the same period to about 90 $g\ l^{-1}$, large areas of the lake bed were exposed, and several islands used by birds as breeding and refuge sites became peninsulas (Patten *et al.* 1987). The contingent effects were that growth and reproduction of several species were reduced (e.g. Herbst 1988; Herbst *et al.* 1988), alkali dust was blown from the exposed lake bed during windy conditions, and predators gained access to the islands. The ecology of some significant migrant waterfowl (especially Wilson's phalarope and the eared grebe) was also threatened. These effects seriously degraded aesthetic and recreational values of the lake, and sparked much public debate. The result of the debate was that diversions have been curtailed for the present, the water level has stabilized, and the lake retains most of its original values. It is now the central landscape feature in an area visited increasingly by national and international tourists for its natural beauty (Hart 1996).

Lake Eyre

Lake Eyre is a very large (approximately 10 000 km^2) episodic salt lake in arid central Australia (Williams 1990). Within the last 100 years, it contained substantial amounts of water in 1949/1950, 1974/1978, 1984/1985, 1985/1986, 1997 and 2000. The lake fills from northern rivers and progressively dries from the north over a period of several months to over a year. Between inundations, it is quite dry and its bed is either a saliniferous mud crust or a thick halite one. When the lake contains water, salinities vary spatially and temporally; they are lowest near the northern inflow areas and increase southwards (Williams & Kokkinn 1988). When the lake first fills, salinities increase rapidly as the saline material on the bed of the lake is dissolved (Williams & Kokkinn 1988). Thereafter, salinities fall as more water enters the lake, but then increase as evaporation decreases the volume of water present. Thus, salinities in the lake vary from <50 to >300 g l^{-1}. The dominant ions are Na^+ and Cl^-. Biodiversity is low and the biota shows little if any regional restrictions in distribution; the fauna at least appears to be part of a widespread central Australian salt lake fauna. The principal values of the lake are aesthetic, scientific and for conservation. With regard to the last value, the lake is a potential breeding site for the banded stilt (*Cladorhynchus leucocephalus)*, a wading bird endemic to Australia (Williams 1990).

This lake is largely unaffected by human activities, and its values remain more or less intact. However, pastoral activities and irrigated agriculture within its catchment have the potential to affect the quality, quantity and pattern of run-off to the lake and thus its ecology. Moreover, it is likely that global climate change and atmospheric changes will affect it, though exactly how remains indeterminate. One prediction of interest in this context is that future rainfall events in central Australia are predicted to be shorter, more intense and larger in total volume. Clearly, this will impact on the natural hydrological cycle of the lake. Perhaps the more frequent filling of the lake in the latter half of the last century is a harbinger of future trends. During the first half of that century, the lake filled only once (1949/1950), an event then regarded as unique. Since that event, the lake has filled five times. In similar vein, Lake Torrens, a large dry playa lake south of Lake Eyre, filled completely in 1989 yet had never filled within historical times (Williams *et al.* 1998). With regard to atmospheric changes, note that when Lake Eyre is full, its maximum depth is less than 6 m (Williams 1990) so that few opportunities exist for its biota to escape increased levels of UV-B. Again, what effects this will have on the biota remain uncertain but they are likely to be adverse.

One impact that humans have had on this lake involves the interaction between the silver gull and the banded stilt. The gull is a significant predator of eggs and chicks of the stilt and its populations have increased following increases in the number of rubbish dumps near townships. The additional predation pressure may well pose a serious threat to the long-term survival of the stilt.

The several values of Lake Eyre have at least been partially recognized by the South Australian government who have included the bed of Lake Eyre North within a national park. Attempts to have the lake and its catchment protected more fully have not succeeded mainly because of opposition from farming and mining interests. However, a recent agreement (The Lake Eyre Basin Agreement) between governments to manage a major portion of the catchment of Lake Eyre to minimize impacts offers some hope that the values of the lake will be maintained.

Lake Cantara South

Lake Cantara South is a small (144 ha), shallow (maximum depth, 0.5 m), temporary salt lake located about 200 km south-east of Adelaide in semi-arid South Australia. It usually contains water between May and early January (8 months from autumn through to early summer) and is dry outside this period with a bed of saline sand and mud. Salinity varies seasonally from <50 to >300 g l^{-1}; typically it is high (>100 g l^{-1}) just after the lake fills and the saline crust has dissolved, low (<50 g l^{-1}) during most months when water is present, and high (>300 g l^{-1}) shortly before the lake dries (Williams 1991). The dominant ions, irrespective of salinity, are Na^+ and Cl^-. Biodiversity and biological production is relatively high and the fauna shows a considerable degree of regional endemism (Williams 1991). The lake lies within a national park and its principal values are aesthetic, scientific and for conservation.

There are no obvious human influences on the lake, it remains relatively undisturbed, and most of its values are intact. Some disturbance may be caused by extensive drainage activities being undertaken within the region but outside the boundaries of the national park. To what extent the lake will remain undisturbed is uncertain given predicted climate and atmospheric changes. If, as some climate models predict, seasonal differences in rainfall in the area become less pronounced with significant amounts of rain in summer, major disturbance to present seasonal cycles in the ecology of the lake will occur. One possibility is that following a large summer filling of the lake, a significant emergence of the aestivating biota could occur but not reproduce before the high rates of summer evaporation dried the lake again. Several events like this would deplete the 'seed bank' so that no emergence would be possible when natural conditions occur. The maximum depth of Lake Cantara South is much less than that of Lake Eyre (Williams 1991) so that the effects of increasing exposure to UV-B in the lake will be even greater.

THE FUTURE: THE LIKELY STATUS OF INLAND SALINE ECOSYSTEMS IN 2025

Environmental predictions are usually fraught with difficulties, or need to be hedged with alternative possibilities. Even so, 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 will differ between regions and the nature of the lakes involved. For purposes of discussion, salt lakes are considered below as permanent, seasonally-filled, or episodically-filled water bodies. A more general discussion of the future of salt lakes has been given by Williams (1996*b*).

Permanent salt lakes

With the exception of those few permanent salt lakes whose water levels are monitored and managed (e.g. Mono Lake), and the few in areas where secular decreases in aridity have occurred recently, 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. Mention is made of those in the western part of the USA, notably Pyramid and Walker Lakes. It will also the fate of the Aral Sea, the outlook for which looks particularly poor given the present attitudes of the governments of Kazahkstan and Uzbekistan, who regard the conservation of the Aral Sea as no longer economically feasible (UNESCO 2000). 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 was used to justify diversions from the Dead Sea, and 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).

Not all permanent salt lakes have well-defined surface inflows of economic value. Trends in their limnological features are less well documented so predictions are more uncertain. Some intermittent data, however, are available for several in Victoria, Australia and indicate decreasing lake sizes too. 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. It would be surprising if this situation were radically different 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). Other sorts of adverse changes are likely to occur in some of these lakes. The introduction of an exotic coelenterate and ctenophore into the Caspian Sea is likely to change the nature of this lake's food web in the next two decades, with further adverse changes 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 are known to have dried more or less permanently following land-use changes, which will certainly 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 (expected to increase globally by 50 to 100% by 2025; Gleick 1993) are implicated in both events.

Salinization has already increased the number of saline 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 take 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 (Williams 2001). The catchment itself, therefore, serves as the 'sink' for salts leached from it and so accumulates them. Brief reference to this phenomenon was made when discussing the Aral Sea; it was 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 in Australia, the Yellow River in China, and the Colorado River in the USA. All of these rivers now have significantly reduced final discharge values.

Episodically-filled salt lakes

Episodically-filled salt lakes, in other words most temporary and ephemeral salt lakes in arid regions, are at present the least impacted of salt lakes by human activities and it would be reasonable to assume that most would retain their relatively natural status for the next two decades. However, this also assumes limited impact from climate change within the next two decades, and this may not be the case. Several climate models predict that warming will be particularly high and rapid in certain arid regions (IPCC 1996). Other arid regions will be less impacted, or will be so more slowly. Many models predict that central Asia will be warmer and drier within the next few decades, whereas Australian arid regions will become warmer but wetter. Whatever the case, it should be stressed that considerable differences exist between models concerning regional predictions. Irrespective of what happens, it is certain that 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 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 1996).

DISCUSSION

Salt lakes are therefore threatened by many human activities, all with effects that reduce their values as natural assets. Already, many salt lakes have been impacted and degraded, almost all irreparably. Degradation continues and is accelerating because of increasing human population densities in semi-arid regions and the concomitant expansion of activities to support them, notably drainage, irrigation and land-use changes. There is little doubt that by 2025 the natural character of most of the world's salt lakes will have changed. 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 Kazahkstan, Uzbekistan, Turkmenistan and other smaller states in the region.

Objective analyses of the benefits and costs of 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 sectoral value, are judged to outweigh the indeterminate costs of conserving and protecting the lake, which is often of more regional, wider value. Retrospective recognition of unpredictable effects or a loss of values, some of global significance, is cold comfort.

The problem is compounded by the failure of international, intergovernmental bodies properly to recognize the importance of salt lakes as integral elements of the world's set of inland aquatic ecosystems. Thus, the influential 'World Water Vision' advanced at the Second World Water Forum at The Hague in the year 2000, did not refer to salt lakes (Cosgrove & Rijsberman 2000). 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. Relatively few countries that are signatories to the Ramsar Convention list salt lakes (particularly temporary ones) as sites of importance. Note, too, that most of the countries that are still not parties to the Ramsar Convention are semi-arid and arid. Thus, overall, salt lakes are under-represented as Ramsar sites.

How can this situation be redressed? The first and most obvious step to be taken involves the need to raise the awareness of both local and the wider community and governmental bodies at all levels to:

- the many values of salt lakes;
- the nature of threats to and impacts on salt lakes arising from human activities and their resultant effects; and
- the differences between salt and freshwater lakes, and the special requirements needed to manage salt lakes sustainably.

Raised awareness is merely the first step. Subsequent steps must involve the implementation of effective local, national and international management and conservation measures designed to mitigate and minimize the adverse impacts of human activities on salt lakes and wherever possible to 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 current preparations of a 'World Lake Vision' by several international groups (e.g. the International Lake Environment Committee [ILEC] and the Global Water Partnership [GWP]) is essential. Better recognition by the Ramsar Convention and the Convention on Biological Diversity, and in national wetland strategy documents, is also needed. The recent foundation of the International Society for Salt Lake Research (http://ISSLR.org) should be of value in achieving this recognition.

Mono Lake, California, provides an outstanding example of what is possible once the total set of values for a salt lake is properly recognized. Its conservation and management offers an invaluable lesson and some hope. As discussed in detail above, inflows to it were diverted to provide additional water to the city of Los Angeles but diversions stopped in the 1990s, so preserving the lake. What factors were important in stopping the diversions? The first and most important was the commitment of a local conservation body and a few individuals in particular (The Mono Lake Committee). Their efforts were intense and maintained over many years (Hart 1996). There were many difficulties. A second factor was their ability freely to bring their point of view to the attention of the wider community. Finally, there was a legal system that judged the conflicting points of view objectively and took serious account of non-economic arguments, and a legislature that implemented the judicial determination.

Regrettably, not all of the factors that brought about the conservation of Mono Lake are in place in many localities where salt lakes occur. In addition, many salt lakes are a good deal more remote than Mono Lake, or not as large. The only hope of conserving many such lakes lies in the application of international pressure. There is also another difficulty: the value of many salt lakes (particularly episodically-filled ones in arid regions) may lie more in their role as part of a mosaic within a wide landscape than as an individual lake. The protection of such lakes will be especially difficult.

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References

Aladin, N.V., Filippov, A.A., Plotnikov, I.S., Orlova, M.I. & Williams, W.D. (1998) Changes in the structure and function of biological communities in the northern part of the Aral Sea (Small Aral Sea), 1984–1994. *International Journal of Salt Lake Research* **7**: 301–343.

Aladin, N.V. & Plotnikov, I.S. (1993) Large saline lakes of former USSR: a summary review. *Hydrobiologia* **267**: 1–12.

Alcocer, J. & Escobar, E. (1990) The drying up of the Mexican Plateau axalapazcos. *Salinet* **4**: 44–46.

Alcocer, J. & Williams, W.D. (1996) Historical and recent changes in Lake Texcoco, a saline lake in Mexico. *International Journal of Salt Lake Research* **5**: 45–61.

Bayly, I.A.E. (1967) The general biological classification of aquatic environments with special reference to those in Australia. In: *Australian Inland Waters and their Fauna: Eleven Studies,* ed. A.H. Weatherley, pp. 78–104. Canberra, Australia: Australian National University Press.

Bohrer, B., Heidenreich, H., Schimmele, M. & Schultze, M. (1998) Numerical prognosis for salinity profiles of future lakes in the opencast mine of Merseburg-Ost. *International Journal of Salt Lake Research* **7**: 235–260.

Bowler, J.M. (1981) Australian salt lakes. A palaeohydrologic approach. *Hydrobiologia* **82**: 431–444.

Browne, R.A. & Bowen, S.T. (1991) Taxonomy and population genetics of *Artemia*. In: *Artemia Biology,* ed. R.A. Browne, P. Sorgeloos & C.N.A. Trotman. Boca Raton, USA: CRC Press.

Carmouze, J.-P. & Pedro, G. (1977) Contribution des facteurs geographiques et sedimentologique a la regulation saline d'un milieu lacustre. *Cahiers ORSTOM (Hydrobiologie)* **11**(3): 231–237.

Clarke, F.W. (1920) *The Data of Geochemistry*. US Geological Bulletin No. 695.

Cole, G.A. (1968) Desert limnology. In: *Desert Biology*, ed. G.W. Brown Jr. New York, USA: Academic Press.

Collins, N.C. (1977) Ecological studies of terminal lakes – their relevance to problems in limnology and population biology. In: *Desertic Terminal Lakes,* ed. D.C. Greer. Logan, Utah, USA: Utah Water Resources Laboratory.

Cosgrove, W.J. & Rijsberman, F.R. (2000) *World Water Vision. Making Water Everybody's Business.* London, UK: Earthscan Publications.

Dana, G.L., Jellison, R., Melack, J.M. & Starrett, G.L. (1993) Relationships between *Artemia monica* life history characteristics and salinity. *Hydrobiologia* **263**: 129–143.

Dumont, H. (1995) Ecocide in the Caspian Sea. *Nature* **377**: 673–674.

Eugster, H.P. & Hardie, L.A. (1978) Saline lakes. In: *Lakes: Chemistry, Geology, Physics,* ed. A. Lerman. New York, USA: Springer-Verlag.

Evans, R.S. (1989). Saline water disposal options in the Murray Basin. *BMR Journal of Australian Geology and Geophysics* **11**: 167–185.

Geddes, M.C. & Williams, W.D. (1987) Comments on *Artemia* introductions and the need for conservation. In: *Artemia Research and its Applications*, Volume 3, ed. P. Sorgeloos, D.A. Bengston, W. Decleir, & E. Jaspers, pp. 19–26. Wetteren, Belgium: Universa Press.

Gleick, P.H., ed. (1993) *Water in Crisis. A Guide to the World's Fresh Water Resources.* New York and Oxford: Oxford University Press.

Groombridge, B. & Jenkins, M. (1998) *Freshwater Biodiversity: a Preliminary Global Assessment. WCMC Biodiversity Series Number 8.* Cambridge, UK: World Conservation Monitoring Centre, World Conservation Press.

Hammer, U.T. (1986) *Saline Lake Ecosystems of the World.* Dordrecht, the Netherlands: Kluwer.

Hammer, U.T. (1990) The effects of climate change on the salinity, water levels and biota of Canadian prairie saline lakes. *Verhandlungen InternationaleVereinigung für Limnologie* **24**: 321–326.

Hart, J. (1996) *Storm over Mono. The Mono Lake Battle and the California Water Future.* Berkeley, CA, USA: University of California Press.

Herbst, D. (1988) Scenarios for the impact of changing lake levels an salinity at Mono Lake: Benthic ecology and the alkali fly, *Ephydra (Hydropyrus) hians* Say (Diptera: Ephydridae). Section 2, Appendix D-2. In: *The Future of Mono Lake*, ed. D. Botkin *et al.* Los Angeles, USA: University of California Water Center Report No. 68.

Herbst, D., Conte, F.P. & Brookes, V.J. (1988). Osmoregulation in an alkaline salt lake insect, *Ephydra (Hydropyrus) hians* Say (Diptera: Ephydridae) in relation to water chemistry. *Journal of Insect Physiology* **34**: 903–909.

Hurlbert, S.H. & Flores, E. (1988) Nesting and conservation of flamingos in the central Andes. Proceedings of IV International Conference on Salt Lakes, Banyules, 28 May 1988.

IPCC (1996) *Climate Change 1995.* Cambridge, UK: Cambridge University Press.

Jellison, R. & Melack, J.M. (1993) Meromixis in hypersaline Mono Lake, California. 1: Vertical mixing and density stratification during the onset, persistence, and breakdown of meromixis. *Limnology and Oceanography* **38**: 1008–1019.

Kosarev, A.N. & Yablonskaya, E.A. (1994) *The Caspian Sea.* The Hague, the Netherlands: SPB Academic Publishing.

Langbein, W.B. (1961) Salinity an hydrology of closed basins. Geological Survey Professional Paper 412.

Letolle, R. & Mainguet, M. (1993) *L'Aral.* Paris, France: Springer-Verlag.

Likens, G.E. & Bormann, F.H. (1974) Acid rain: a serious regional environmental problem. *Science* **184**: 1176–1179.

Mitchell, B.D. & Geddes, M.C. (1977) Distribution of the brine shrimps *Parartemia zietziana* (Sayce) and *Artemia salina* (L.) along a salinity and oxygen gradient in a South Australian salt-field. *Freshwater Biology* **7**: 461–467.

Moss, B.R. (1998) *Ecology of Fresh Waters. Man and Medium, Past to Future.*Third edition. Oxford, UK: Blackwell Science.

Oren, A., ed. (1999) *Microbiology and Biogeochemistry of Hypersaline Environments.* Boca Raton, CA, USA: CRC Press.

Patten, D.T., Conte, F.P., Cooper, W.E., Dracup, J., Dreiss, S., Harper, K., Hunt, G.L., Kilham, P., Klieforth, H.E., Melack, J.M. & Temple, S.A. (1987) *The Mono Lake Basin Ecosystem: Effects of Changing Lake Level.* Washington, DC, USA: National Academy Press.

Rawson, D.S. (1946) Successful introduction of fish in a large saline lake. *Canadian Fish Culturalist* November 1946.

Reati, G.J., Florin, M., Fernandez, G.J. & Montes, C. (1997) The Laguna de Mar Chiquita (Cordoba, Argentina): a little known, secularly fluctuating, salt lake. *International Journal of Salt Lake Research* **5**: 187–219.

Reeves, C.C., Jr (1978) Economic significance of playa lake deposits. *Special Publications of the International Association for Sediments* **2**: 279–290.

Robinson, T. & Minton, C. (1990) The enigmatic banded stilt. *Birds International* **1990**: 72–85.

Schroeder, R.A., Setmire, J.G. & Wolfe, J.C. (1988) Trace elements and pesticides in the Salton Sea area, California. In: *Proceedings on Planning for Irrigation and Drainage,* 19–21 July 1988, pp. 700–707. Lincoln, Nebraska, USA: American Society of Civil Engineers, Irrigation and Drainage Division.

Shiklomanov, I.A. (1990) Global water resources. *Natural Resources* **26**: 34–43.

Stine, S. (1990) Lake Holocene fluctuations of Mono Lake, eastern California. *Palaeogeography, Palaeoclimatology, Palaeoecology* **78:** 333–381.

Timms, B.V. (1976) A comparative study of the limnology of three maar lakes in western Victoria. 1. Physiography and physico-chemical features. *Australian Journal of Marine and Freshwater Research* **27:** 35–60.

UNESCO (2000) *Vision for the Aral Sea Basin.* Paris, France: UNESCO.

Walter, M.R., Buick, J.R. & Dunlop, J.S.R. (1980) Stromatolites 3400–3500 Myr old from the North Pole area, Western Australia. *Nature* **284:** 443–445.

Williams, W.D. (1981) Problems in the management of inland saline lakes. *Verhandlungen Internationale Vereinigung für Limnologie* **21:** 688–692.

Williams, W.D. (1990) Salt lakes: The limnology of Lake Eyre. In: *Natural History of the North East Deserts,* ed. M.J. Tyler, C.R. Twidale, M. Davies & C.B. Wells, pp. 85–99. Adelaide, Australia: The Royal Society of Adelaide.

Williams, W.D. (1991) Saline lake microcosms (microecosystems) as a method of investigating ecosystem attributes. *Verhandlungen Internationale Vereinigung für Limnologie* **24**: 1134–1138.

Williams, W.D. (1993*a*) Conservation of salt lakes. *Hydrobiologia* **267**: 291–306.

Williams, W.D. (1993*b*) The worldwide occurrence and limnological significance of falling water-levels in large, permanent saline lakes. *Verhandlungen Internationale Vereinigung für Limnologie* **25:** 980–983.

Williams, W.D. (1995) Lake Corangamite, Australia, a permanent saline lake. Conservation and management issues. *Lakes and Reservoirs: Research and Management* **1**(1): 55–64.

Williams, W.D. (1996*a*) The largest, highest and lowest lakes of the world: saline lakes. *Verhandlungen Internationale Vereinigung für Limnologie* **26:** 61–79.

Williams, W.D. (1996*b*) What future salt lakes. *Environment* **38** (9): 12–20, 38–39.

Williams, W.D. (1998*a*) *The Management of Inland Saline Waters.* Kusatsu, Japan: ILEC/UNEP.

Williams, W.D. (1998*b*) Salinity as a determinant of the structure of biological communities in salt lakes. *Hydrobiologia* **381**: 191–201.

Williams, W.D. (1999) Salinisation: A major threat to water resources in the arid and semi-arid regions of the world. *Lakes and Reservoirs: Research and Management* **4:** 85–91.

Williams, W.D. (2001) Salinization: unplumbed salt in a parched landscape. *Water Science and Technology* **43**(4): 85–91.

Williams, W.D. (2002) Anthropogenic salinisation. *Hydrobiologia* (in press).

Williams, W.D. & Aladin, N.V. (1991) The Aral Sea: recent limnological changes and their conservation significance. *Aquatic Conservation: Marine and Freshwater Ecosystems* **1:** 3–23.

Williams, W.D., De Deckker, P. & Shiel, R.J. (1998) The limnology of Lake Torrens, an episodic salt lake of central Australia, with particular reference to unique events in 1989. *Hydrobiologia* **384:** 101–110.

Williams, W.D. & Kokkinn, M.J. (1988) The biogeographical affinities of the fauna in episodically filled salt lakes: A study of Lake Eyre South, Australia. *Hydrobiologia* **158:** 227–236.

Zeeb, B.A. & Smol, J.P. (1995) A weighted-averaging regression and calibration model for inferring lakewater salinity using chrysophycean stomatocysts from lakes in western Canada. *International Journal of Salt Lake Research* **4**(1): 1–23.

Zenkevitch, L. (1963) *Biology of the Seas of the USSR.* London, UK: Allen and Unwin.