GUIDELINES of LAKE MANAGEMENT

Volume 6

Management of Inland Saline Waters

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FOREWORD

Almost a billion people, including some of the most disadvantaged of the human race, live in dryland regions of the world - that part of our planet receiving on average less than about 500 mm of rain annually. Drylands cover almost a third of the land area of the planet and include substantial regions of all continents, including all of Antarctica. Characteristic features of the natural environment and landscape are salt lakes: temporary or permanent bodies of salt or saline water. They include the largest lake in the world (the Caspian Sea), the lowest (the Dead Sea, over 400 m below ocean level), and some of the highest (those on the Altiplano of South America and on the Tibetan Plateau). Indeed, in both number and volume, salt lakes are a very considerable fraction of the world's inland resources of water. In fact, if one includes the Caspian Sea, salt lakes hold almost as much water as do freshwater lakes; even without considering the Caspian Sea, they are almost as numerous in number.

We typically cannot use water directly from salt lakes for domestic, industrial and agricultural purposes. However, these lakes and other smaller ones have many more direct and important economic uses. They include being a source of salt and other minerals, and a source of plant and animal products (including fish in lakes of moderate salinity). Non-economic values also are important, as many salt lakes are frequently of cultural significance, of high aesthetic appeal, attractive to tourists and of great interest to scientists. All but the most saline of these lakes have a diverse flora and fauna.

Notwithstanding their many uses and values, their widespread global occurrence, and their number and the volume of water they hold, salt lakes are under threat almost wherever they exist. They have been, and are being, drained, polluted, significantly altered and over-exploited. We have already lost a significant part of our natural environment and in grave danger of losing more. We have particularly impoverished, and will further impoverish, those who live in drylands areas.

Why has this happened and why do we allow it to continue? There are many explanations for this situation. One reason is certainly *ignorance*; we have largely focused our attention on freshwater resources, and have not fully appreciated the many values and attributes of salt lakes. Our management of salt lakes, consequently, has been both inadequate and inept to date.

It is to address this situation that this present book has been prepared. It explicitly points to the global importance and widespread occurrence of salt lakes, it identifies their many uses and values, it summarizes what we know about them as far as their major physico-chemical and biological features are concerned, and it discusses seven important case studies. In doing this, it lays the foundations of effective management; namely recognition and understanding of these important natural resources.

The book is a significant addition to the ILEC series on Guidelines of Lake Management, and is recommended to all those interested in salt lakes, be they conservationists, scientists, or managers. It is the hope that it will prove to be informative, useful, and, above all, contribute to our management of salt lakes. The author, Emeritus Professor W.D.Williams, a vice-chairman of the ILEC scientific committee, brings to bear a lifetime's exploration of salt lakes in developing this book, and has our thanks in completing this volume.

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CHAPTER 1

INTRODUCTION

1.1 SCOPE

Although limnology is often defined as the study of inland fresh waters, a large proportion of inland water-bodies is saline and a better definition is that limnology is the study of inland fresh and saline waters. Whatever the definition, most limnological studies of inland waters are nevertheless concerned with fresh waters. This simply reflects two facts. First, fresh waters are much more important in temperate parts of the northern hemisphere than salt waters and it is in these regions that most limnological investigations have been carried out and, indeed, where limnology has its historical roots. Second, fresh water is economically more useful to human beings than salt water and therefore more likely to attract the attention of researchers.

Perhaps an additional reason for the relative paucity of investigations of salt waters is the fact that even until quite recently many salt lakes were regarded as aberrant ecosystems, sterile and lifeless environments of little economic value apart from their minable deposits, and of low scientific interest. Such perceptions are grossly in error as a large and increasingly voluminous literature attests. It is now abundantly clear that salt lakes have a large number of commercial and other values, are of high scientific interest, and possess a diverse biota of which much is regionally endemic. Even so, old perceptions die hard, and in the absence of easily available books and guides about salt lakes, many such water-bodies have been badly managed, many of their values have been irreparably and significantly degraded, and few receive the attention accorded many freshwater lakes, rivers and streams (cf. Wetzel, 1987).

It is this situation which has prompted the preparation of the present book in ILEC's Guidelines of Lake Management. The broad aim is to draw attention to the wide geographical spread of saline lakes, highlight their many values - economic, scientific and otherwise -, sketch some of the more important physico-chemical and biological features, and, not least, proffer some management advice. To provide focus for this broad aim, the book discusses several case studies involving important saline lakes where mismanagement (or at least a lack of attention to basic principles) has resulted in serious diminishment of lake values.

The book is not unique in the general nature of its subject matter, but is unique in the nature of the audience for which it is intended: governments, local authorities, water resource managers, and conservationists. In short, it is intended for those in whom the broader community has placed its trust to manage and conserve natural resources - in this case, salt lakes - for the wider benefit. Of books intended for a more scientific readership, mention is made of those by Kiener (1978), Hammer (1986) and Javor (1989). For a variety of reasons (language, scope, accessibility, cost), these are less useful for the present target audience than might have been the case. There are also many specialized books dealing with particular components of salt lake ecosystems or individual lakes. Mention will be made of these in the body of the text as occasion demands. The proceedings of the triennial symposia on salt lakes (commencing in 1979 and published in special volumes of *Hydrobiologia*) and the *International Journal of Salt Lake Research* provide ongoing and particularly useful sources of information on salt lakes and address a wide range of scientific topics.

Finally in these introductory remarks, it is important to be clear about the sorts of water-body that fall within the book's ambit.

Two main types of saline water exist on earth: the sea, and continental salt waters lacking any direct connection to the marine environment. These inland saline waters are conveniently referred to as *athalassohaline* waters or saline *epicontinental* waters. The term athalassohaline has its origins in the term *athalassic* coined by Bayly in 1967 to refer to inland or coastal bodies of water presently lacking any direct marine connection. This book is mainly about athalassohaline waters. However, as appropriate, it also deals with some bodies of salt water which represent cut-off remnants of the sea which have never dried (the Caspian is the most notable example), and coastal, salt producing ponds of high salinity (solar salt ponds) fed by sea-water. Saline waters which consist of contemporary mixtures of sea-water and fresh water and with correspondingly intermediate salinities are not dealt with. These are *brackish* waters and the most obvious examples are estuaries.

1.2 THE DISTINCTION BETWEEN FRESH AND SALINE WATERS AND SOME TERMS

All inland waters contain some dissolved salts. The total concentration of these salts is the *salinity* of the water. The question is: what value of salinity distinguishes fresh from saline water? Of course, there is no difficulty in recognizing highly saline waters, viz. those with large amounts of dissolved salts and markedly salty to human taste, and quite fresh waters, viz. those with negligible amounts of dissolved salts and with no indication of saltiness to human taste. But is there a particular value for salinity which can be used unequivocally to demarcate fresh and saline waters and which is based on firm biological or physico-chemical criteria? The answer is a resounding one: no. For both biological communities and almost all physico-chemical features, a continuum exists between fresh and saline waters.

Even so, there are clear biological and some marked physico-chemical differences between recognisably 'saline' and 'freshwater' ecosystems and it has proved convenient to adopt a value for salinity, 3 g/L (~3 ppt), above which waters are regarded as saline and below which waters are regarded as fresh. Other demarcatory values, some higher and some lower, have been proposed, but the value of 3 g/L has become the one most widely agreed upon, the conventional one. This value is, coincidentally, the 'calcite branch point', that is, the salinity at which calcite is precipitated as natural waters concentrate. It is also very near the nodal value separating the bimodal values of the frequency distribution of salinity in lakes (Hurlbert, 1994), and the value above which water tastes 'salty' to most people.

Further divisions of saline water into ranges of salinity are equally arbitrary. One proposed by

Hammer (1986) divides saline waters into those that are *hyposaline* (salinity ~3-20 g/L), *mesosaline* (~20-50), and *hypersaline* (>~50). Javor (1989) regarded hypersaline waters as those with salinities in excess of about 70 g/L, but many regard any water with a salinity greater than that of the sea, i.e. 35 g/L, as hypersaline. Since the total range of salinity recorded from salt lakes is from 3 to >500 g/L (the upper value is determined by the ionic composition of the water in question), it will be seen that no matter what definition of hypersaline is accepted the range of salinity in hypersaline waters is considerable.

It is important to note in this connection that water resource managers concerned with the use of water for agricultural, industrial and domestic consumption frequently classify waters into categories of salinity that disagree by almost an order of magnitude in concentration from those used by limnologists. Thus, for many water resource managers, fresh waters are only those with salinities lower than 0.3 g/L, and waters of higher salinity are 'slightly saline' (0.3 - 1.0), 'saline' (1.0 - 3.0), or 'highly saline' (greater than 3.0). This terminology reflects the usefulness of the water for particular purposes.

Many names and terms have been applied to saline lakes, a large number of them of local derivation. To avoid confusion, this book refers generically to most bodies of inland saline water, irrespective of depth or permanency, as saline or salt lakes. Desertic terminal lakes and closed-basin lakes, which are often regarded as synonymous with salt lakes, are terms that will not be used since at least some of these lakes are fresh. Other names often used to refer to inland bodies of salt water (or locations where such bodies may occur) include saline playa lake, saline pan, salina, sabka, liman, and soda, alkali and bitter lakes. These refer to particular types of saline lake according to morphometry, chemical composition, location or region.

Several terms have been used to describe the permanency or otherwise of salt lakes. To avoid confusion and to attempt some standardization with the terms used in connection with fresh waters in dry regions (see Comin and Williams, 1994; Williams, in press a), the following terminology is used here. *Permanent* salt lakes *usually* contain water (if they ever dry out, they do so only infrequently). *Temporary* salt lakes *frequently* dry out (that is, lack surface water); they comprise *intermittent* salt lakes, which contain water or are dry at more or less predictable times in a year, and *episodic* salt lakes, which contain water more or less unpredictably and are usually dry. The term 'ephemeral' will be avoided since it has been used in connection with both intermittent and episodic salt lakes and its use is likely to cloud the differences between these two distinctly different types of salt lake.

1.3 GLOBAL IMPORTANCE

Given the impermanence of many salt lakes, it is difficult to derive precise global values for the number of salt lakes worldwide and the total volume of inland saline water. Nevertheless, it is clear that this number and volume are not much less than those of inland fresh waters (see Meybeck, 1995). In any event, salt lakes are certainly geographically widespread, as Fig.1.1 indicates and section 1.4 details. They are by no means confined to warm, semi-arid regions of the world as most popular perceptions would have one believe.

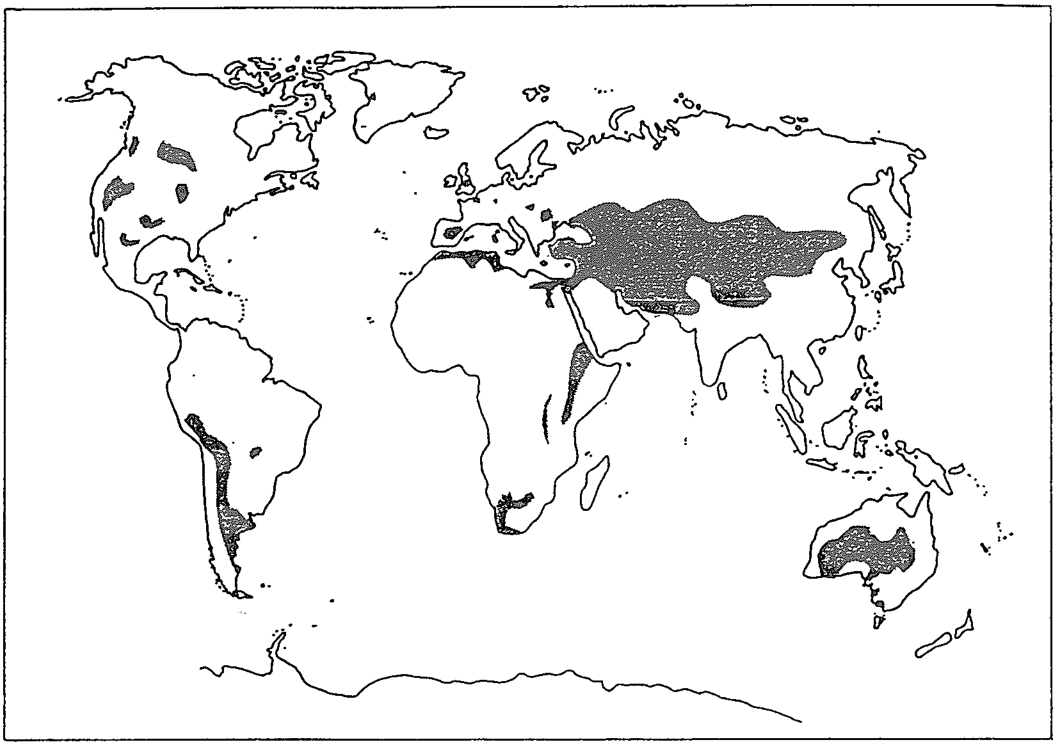

Fig. 1.1 Geographical distribution of major areas with salt lakes. Note: salt lakes occur outside these areas, but not as frequently.

Table 1.1 Global water resources. Simplified from Shiklomanov (1990).

Compartment	Volume ($km^3 \times 10^3$)	Percent total water
Sea	1,338,000	96.5
Groundwater	23,400	1.7
Glaciers, snow, ice	24,364	1.8
Freshwater lakes, rivers, wetlands	105	0.008
Saline lakes	85	0.006
Atmospheric water	13	0.001

Volumes of water in various global compartments are shown in Table 1.1. This indicates that the volume of inland saline water in salt lakes is not significantly less than that of inland fresh water in lakes and rivers. It is, as a percentage of total biospheric water, 0.006 compared to 0.008. Admittedly, some 70 per cent of inland saline water is found in the Caspian Sea, but, then again, some 40 per cent of inland fresh waters are found in the Great Lakes of North America and Lake Baikal, and a single river, the Amazon, carries by far the largest volume of water of any river. Certainly, some of the world's largest lakes (areas >500 km^2) are saline, with by far the largest being saline (Caspian Sea, 422,000 km^2). Other very large saline lakes that are permanent include the Aral Sea (still ~35,000 km^2), Balkhash (22,000 km^2), Issyk-Kul (6,280 km^2) and Qinghai Hu (4,437 km^2) (Herdendorf, 1990). It may also be remarked that the lowest lake on earth is saline (the Dead Sea, 401 m below sea-level) as well as some of the highest (those on the Altiplano of South America and on the Tibetan plateau occur at over 3,000 m above sea-level).

Although salt lakes are not confined to warm, semi-arid regions, aridity - irrespective of prevailing air temperatures - is one of the two formative conditions necessary for the development of salt lakes. In this context, note that about one third of the world land area can be regarded as semi-arid or drier. Salt lakes do not occur uniformly in such regions, being rare in hyper-arid regions for example, but they are nevertheless frequently abundant in such regions. Where they occur, salt lakes are often the most obvious if not the only type of water-body to occur and are a significant feature of the landscape. In various ways, therefore, they are often an important natural resource for local human populations. This importance grows annually as human populations spiral upward in many dry parts of the world and increasingly impact upon nearby resources. Over 600 million people live in semi-arid and arid regions, and high growth rates and severe resource deprivation often characterise their populations. The better management and conservation of salt lakes is of more than academic interest to a significant fraction of the human population.

The global extent of arid and semi-arid regions is indicated in Table 1.2 where, broadly speaking, arid and semi-arid regions are taken to have mean annual rainfalls of 25-200 and 200-500 mm, respectively. Hyper-arid regions, which are generally too dry for the development of any standing waters, have mean annual rainfalls of <25 mm. Only about 6 per cent of world land area is hyper-arid.

Table 1.2 Geographical distribution of arid and semi-arid areas.

After various sources.

Continent	Arid		Semi-arid		Total	
	10^6km^2	%	10^6km^2	%	10^6km^2	%
Africa	6.2	20.4	5.1	16.9	11.3	37.3
America	2.1	4.9	4.7	11.0	6.8	15.9
Middle East	3.0	49.7	1.0	16.0	4.0	65.7
Asia	4.0	10.5	5.3	13.9	9.3	24.4
Australia	3.8	49.0	1.5	20.0	5.3	69.0
Europe	0.0	0.1	0.2	2.3	0.2	2.4
World	19.1	14.1	17.9	13.2	37.0	27.3

1.4 OCCURRENCE

Two conditions must be fulfilled for salt lakes to form. First, there must be a suitable geomorphological depression representing the terminus of a closed drainage basin. Closed drainage basins are referred to as *endorheic* basins; *exorheic* basins, on the other hand, drain to the sea and are characterized by freshwater lakes. Second, there must be a balance between the volume of water flowing into the depression or falling onto it as rain (or snow) and the volume of water evaporating from it or seeping away through sediments. If there is too much inflow water or precipitation on the lake, the lake will overflow and become or remain fresh; conversely, if there is too little inflow and precipitation (and/or too much evaporation and seepage), the lake will simply dry up.

Of course, seasonal climatic events as well as longer term (secular) climatic events ensure the hydrological balance changes. As a result, many salt lakes contain water for only part of a year (*intermittent* salt lakes, see above) or unpredictably after long dry periods (*episodic* salt lakes). Langbein (1961) was the first clearly to recognize the importance of climate for the formation of salt lakes. Figure 1.2 summarizes his ideas and indicates the prevailing climatic conditions near several important salt lakes. In a few cases, salt lakes occur in climatically unsuitable places or in exorheically drained basins. Here, they may be the result of saline discharges from underground or the result of subsidence over salt-mining areas. There are many examples in Europe. Solar salt ponds may also provide exceptions, as do areas of the sea which have been artificially embayed.

With regard to the geomorphological depressions in which salt lakes form, that is, the actual basin where water collects to form the lake, the genesis and evolution of these are almost as diverse as those in which freshwater lakes form. However, glacial and fluviatile processes are generally much less important, and tectonic, volcanic, aeolian (wind), and solution processes more important. And, as with fresh waters, many bodies of salt water have been created by human beings, the most important being solar salt ponds. Others include those created by mining subsidence, those built to act as 'sinks' for excess salts in certain rivers and in underground and irrigation waters (so-called *evaporation ponds*; see section 5.4), and former freshwater lakes that have become saline following the salinization of agricultural land by destruction of the natural vegetation or by excessive irrigation.

The wide geographical occurrence of salt lakes has already been alluded to and an indication of where salt lakes occur has been given by Fig.1.1. Williams (1996a) gives a comprehensive account of this occurrence. In less detail, the major areas of distribution on a continent-by-continent basis are as follows.

In North America (Fig. 1.3), salt lakes occur throughout the western half of the continent as well as widely elsewhere. Six more or less distinct regions can be recognized in which salt lakes are common (but they may be found outside these regions):

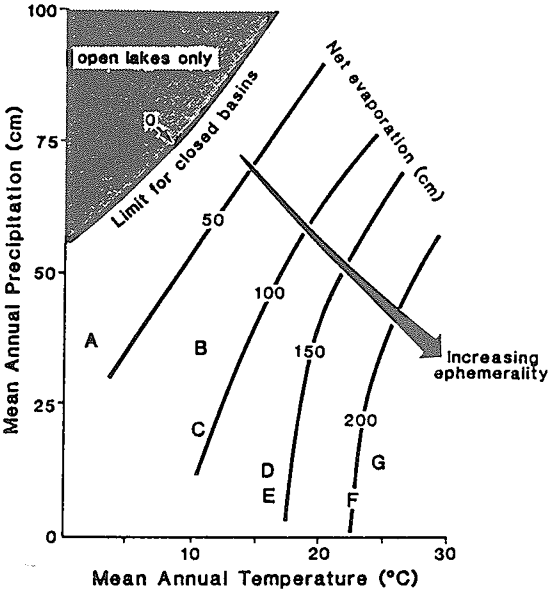

Fig. 1.2 The occurrence of closed lakes in relation to climate. A, saline lakes of Saskatchewan; B, Great Salt Lake, Utah; C, Mono Lake, California; D, Salton Sea, California; E, Owens Lake, California; F, Dead Sea, Israel/Jordan; G, Lake Eyre, Australia. Modified after Langbein (1961) and Cole (1968).

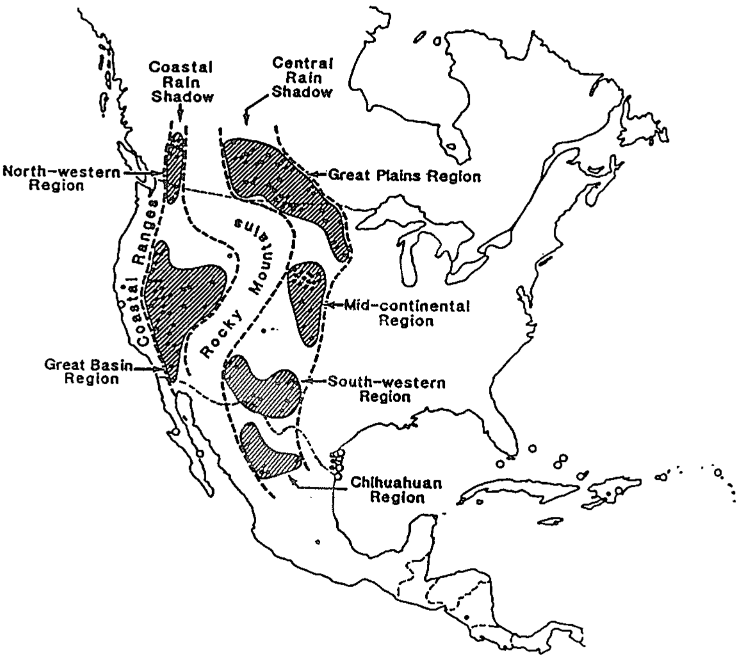

Fig. 1.3 Geographical distribution of salt lakes in North America. Hatched area, general region within which salt lakes occur. Solid circles, athalassic waters; open circles, solar salt ponds and other marine-associated salt waters. From Williams (1996a).

(1) the Great Plains region of southern Saskatchewan and adjacent areas of Alberta, Manitoba, the Dakotas and western Minnesota. Examples: Redberry and Little Manitou lakes.

(2) a north-western region comprising plateaux in southern British Columbia and part of north-central Washington. Examples: lakes Lenore, Hot and Soap.

(3) a Great Basin region comprising all of Nevada, western Utah, parts of Oregon, and a large part of south-eastern California. Examples: Mono Lake (see section 6.6), the Salton Sea, Pyramid Lake, the Great Salt Lake.

(4) a Mid-continental region of western Nebraska and Kansas. Example: Nebraskan sandhill lakes.

(5) a south-western region comprising parts of Texas, southern New Mexico, and eastern Arizona. Example: lakes of the Llano Estacado in Texas.

(6) the Chihuahuan region of northern Mexico. Example: Laguna Salada.

In addition to the salt lakes in these regions, numerous solar salt ponds and other coastally located bodies of salt water occur in North America. Examples: San Francisco Bay salt ponds, Laguna Madre.

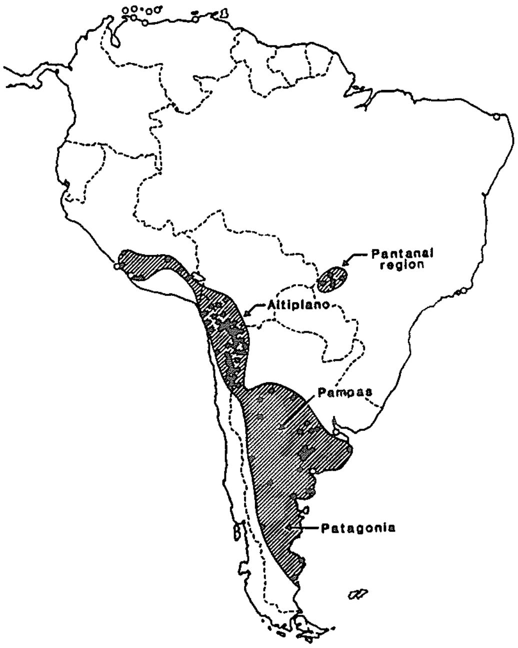

Fig. 1.4 Geographical distribution of salt lakes in South America. Hatched area, general region within which salt lakes occur. Solid circles, athalassic waters; open circles, solar salt ponds and other marine-associated salt waters. From Williams (1996a).

In South America (Fig. 1.4), salt lakes occur in two main regions, the Altiplano and its northern Peruvian extension, and the pampas of central Argentina and northern Patagonia. In both regions they are usually shallow and temporary. On the Altiplano, they occur at high altitude (3,000 m or higher above sea-level). Examples: lakes Uyuni and Poopo. Pampas salt lakes occur at much lower altitudes (<500 m above sea-level) but are more extensively distributed. Example: Mar Chiquita (see section 6.7). Salt ponds are numerous along the coast of Venezuela and on off-shore islands.

In Europe (Fig. 1.5), saline water-bodies in the west and north-west result from saline springs, salt mining or have marine associations. It is only in southern and south-eastern Europe, with its warmer and drier climate, that continental salt lakes and solar salt ponds are found. Examples: Lake Gallocanta (Spain), Camargue lakes (France), Seewinkel lakes (Austria).

In Africa (Fig. 1.6), salt lakes are widespread, if somewhat scattered, through all the northern countries bordering the Mediterranean Sea. Example: Lake Quarun. Those in the Sahara are much more scattered - a reflection of the hyper-aridity of much of this region. Salt lakes in eastern Africa concentrate in a strip stretching from the Red Sea through Ethiopia and Kenya to Tanzania. Most if not all of these salt lakes occur within or are associated with the Great Rift Valley and the Western Rift Valley. Examples: lakes Nakuru, Bogoria. Salt lakes in southern Africa mostly take the form of shallow, temporary water-bodies though an important exception is the Pretoria Salt Pan, a permanent salt lake.

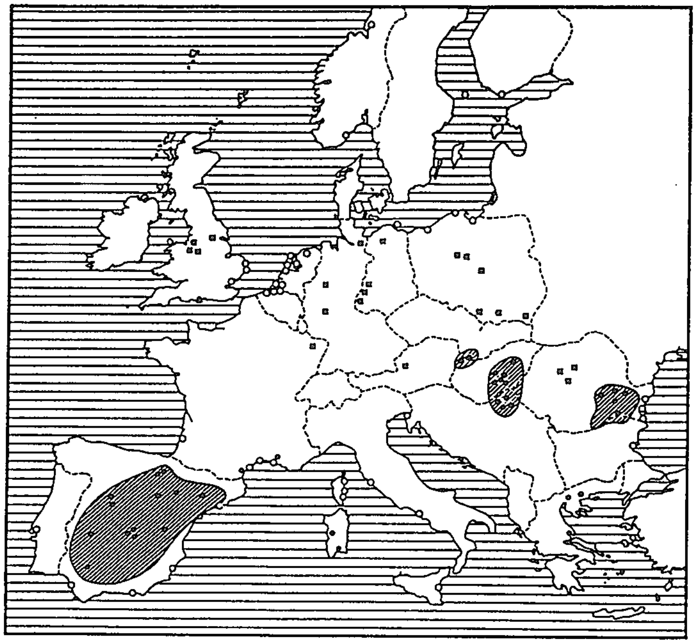

Fig. 1.5 Geographical distribution of salt lakes in Europe. Hatched area, general region within which salt lakes occur. Solid circles, athalassic waters; solid squares, waters with salts derived from underground sources; open circles, solar salt ponds and other marine-associated waters. From Williams (1996a).

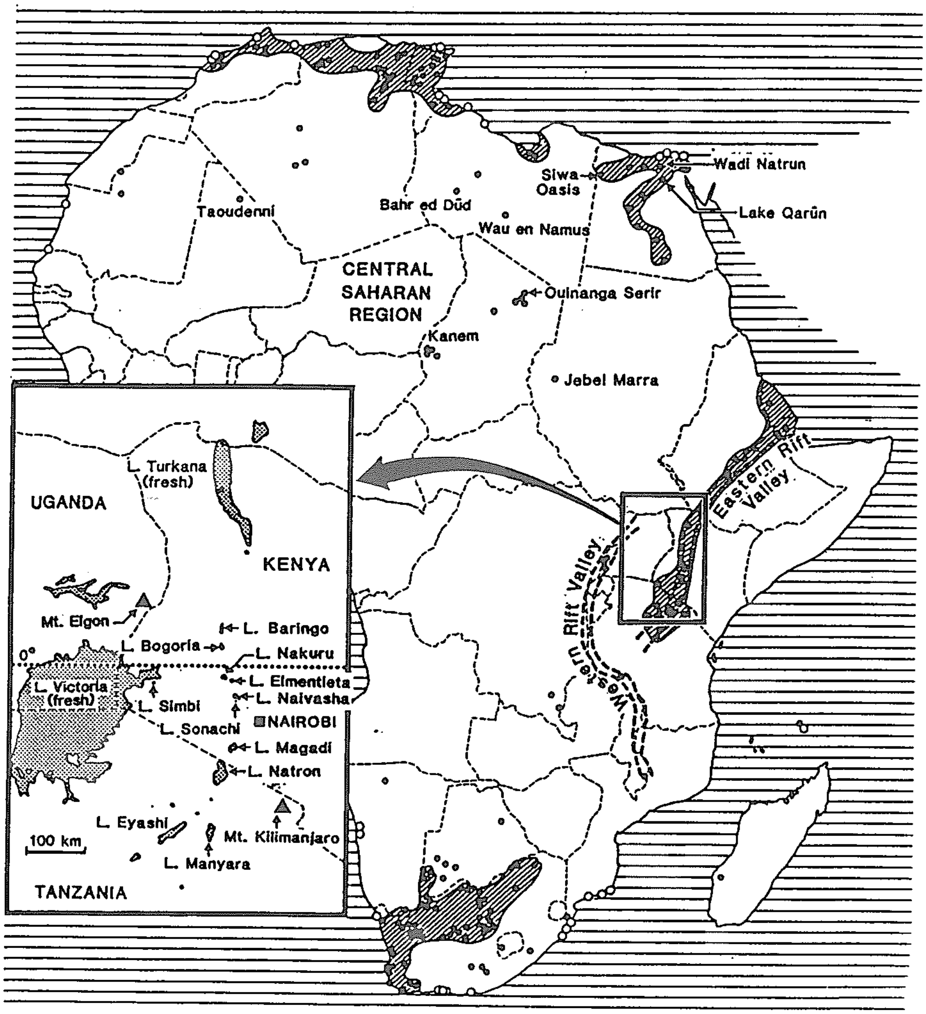

Fig. 1.6 Geographical distribution of salt lakes in Africa. Hatched area, general region within which salt lakes occur. Solid circles, athalassic waters; open circles, solar salt ponds and other marine-associated salt waters. From Williams (1996a).

Salt lakes in Asia (Fig. 1.7) occupy an exceedingly extensive region stretching from Turkey in the west to China in the east. In the Middle East, the best known salt lake is the Dead Sea of Israel and Jordan (see section 6.4), but several other large, permanent salt lakes are to be found here. Example: Lake Van. Many lakes of Central Asia, likewise, are large and permanent. Examples: Caspian and Aral Seas (see section 6.2), lakes Balkhash and Issyk-Kul. There are also many shallow, temporary salt lakes in the same region. In China, five regions may be identified where salt lakes are common: Inner Mongolia, Qaidam Basin, north

Qinghai, Qinghai-Tibetan plateau, and Sinkiang. Over 50 per cent of total lake area in China is provided by salt lakes, of which one, Qinghai Hu, is the largest Chinese lake (see section 6.3). On the other hand, salt lakes are not common in India; the largest number occur in Rajasthan, north-eastern India. Example: Sambhar Salt Lake. They are common on the Iranian plateau although not well known. Example: lakes Urmia and Niriz.

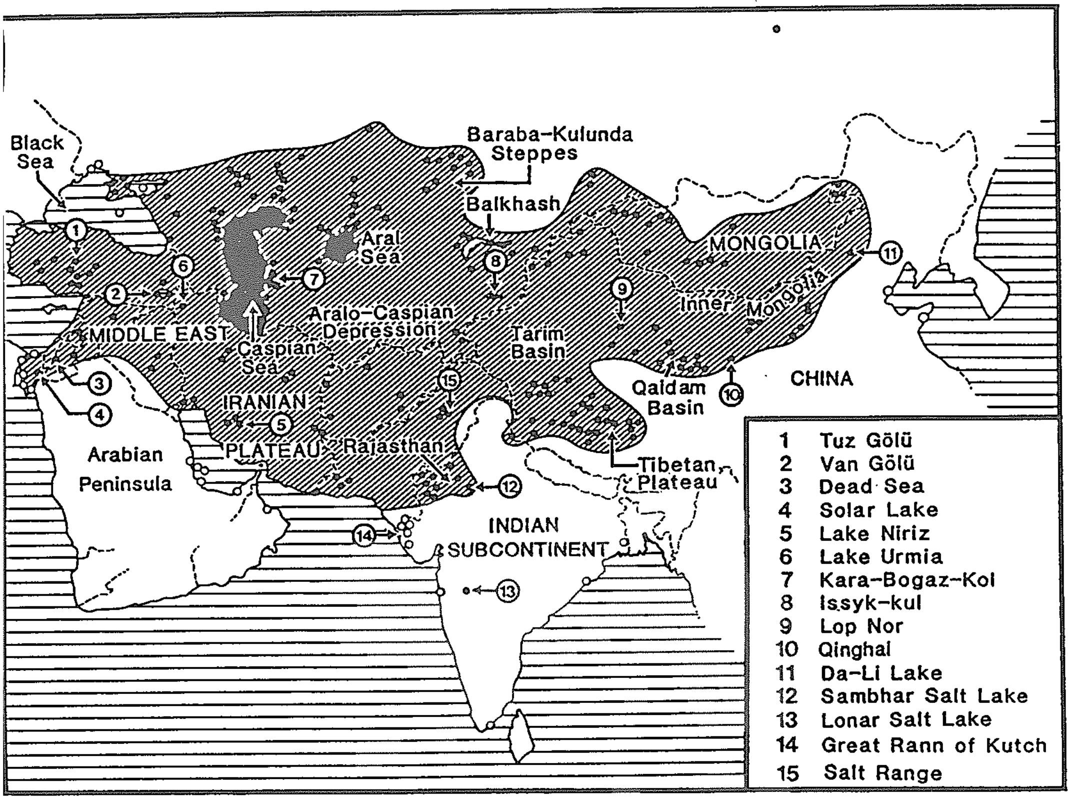

Fig. 1.7 Geographical distribution of salt lakes in Asia. Hatched area, general region within which salt lakes occur. Solid circles, athalassic waters; open circles, solar salt ponds and other marine-associated salt waters. Some notable lakes are numbered. From Williams (1996a).

Salt lakes in Australia (Fig. 1.8) are numerous, as befits a generally arid continent, and more or less easily divide into, first, permanent and intermittent salt lakes of south-eastern and south-western Australia, and, second, episodic salt lakes of the Australian interior. By far the largest example of the latter is Lake Eyre, but Lake Corangamite, a permanent salt lake in south-eastern Australia, is by no means small, and is indeed the largest natural body of permanent water on the Australian mainland (see section 6.5).

Finally, with regard to continental salt lakes, brief mention should be accorded those in Antarctica. There, they are known from some twenty isolated and ice-free 'oases' ranging in size from ~25 to 2,000 km^2 and located mostly along the east coast. A variety of lake types occur in these oases, not all saline. A few of the salt lakes are intermittent and are dry in summer. Of permanent salt lakes, some are continuously frozen solid, others are covered by surface ice except marginally during a short summer, others are free of surface ice in summer, and yet others never freeze because of their extremely high salinities (which sufficiently depress the freezing point to prevent the formation of ice). Example: Lake Vanda. There are no equivalent salt lakes in the Arctic, although a few salt lakes are known from the region, including a few slightly saline ones in Greenland.

In addition to salt lakes on continental land-masses, many small bodies of salt water with salinities greater than that of the sea occur on several oceanic islands. Some, so-called *anchialine ponds*, maintain a hydrological continuity with the nearby marine environment.

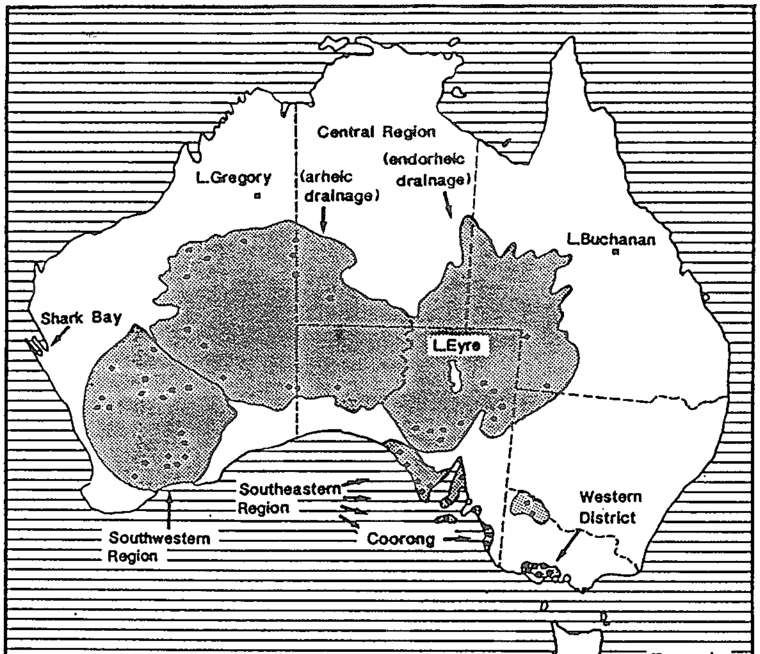

Fig. 1.8 Geographical distribution of salt lakes in Australia. Hatched area, general region within which salt lakes occur. Solid circles, athalassic waters; solid squares, notable salt lakes outside of major regions of salt lake distribution. From Williams (1996a).

CHAPTER 2

CHEMICAL AND PHYSICAL FEATURES

2.1 SALINITY

Salinity is a key chemical feature in salt lakes since it is an important determinant of many other features, physical, chemical and biological. It is important, therefore, to understand clearly what is meant by the term salinity, to know how to measure it, and to be aware of the difference between units used in expressing values of salinity. Williams and Sherwood (1994) discuss these matters in more detail than can be done here.

Salinity, as used by limnologists, is the concentration of all dissolved salts, that is, the sum total of all ion concentrations, or total ion composition. It is not to be confused with the so-called Practical Salinity Scale of modern oceanographers (expressed in dimensionless units), since this is based upon marine waters of constant ionic composition.

Clearly, the only exact way to determine salinity is to determine the concentrations of all individual ions and to sum the values. In salt lakes, as in fresh waters, these ions are mostly Na^+, K^+ Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^- and CO_3^{2-}. Minor amounts of other ions (e.g. NO_3^-, PO_4^{2-}) also occur. This analytical process, it need hardly be said, involves much tedious and time-consuming effort. Fortunately, several simpler, surrogate measures of salinity exist, all of reasonable accuracy. These are generally used in place of full ion analyses.

The most important surrogate measures involve determination of density, electrical conductivity, freezing point depression, and total dissolved solids or matter (or total filterable residue). None of these can provide exact values for salinity since values for density, conductivity and freezing point depression are determined in part by the proportions of ions present (which vary between lakes, and, without a full ion analysis, remain unknown), and the concentration of total dissolved solids represents dissolved salts (i.e. salinity) and an unknown concentration of dissolved organic matter. Nevertheless, since the waters of many salt lakes are dominated by Na^+ and Cl^- ions, reasonable approximations to actual salinities are frequently possible by reference to the density, conductivity and freezing point depression of sodium chloride solutions. Table 2.1 provides data on these parameters for various concentrations of sodium chloride.

Density can be determined directly by gravimetric methods or indirectly by hydrometers (sometimes marketed as salinometers). Since the density and refractive index of a liquid are correlated, refractometers (instruments to measure refractive index) may also be used to provide a measure of salinity based on density. Field refractometers are available which are robust, cheap, relatively accurate and give direct readings for salinity.

Table 2.1 Some properties of aqueous solutions of sodium chloride over a range of concentrations. After various sources but compiled largely from Weast (1968).

Concentration[1] ppt	Concentration[2] g/L	Density[3] D_{20}	Density[4] °Bé	Conductivity[5] mS_{20}	Δ[6] °C
0.0	0.0	1.0000	0.00	0.0	0.00
5.0	5.0	1.0035	0.51	8.2	0.30
10.0	10.1	1.0071	1.02	16.0	0.59
15.0	15.1	1.0107	1.53	23.2	0.89
20.0	20.2	1.0143	2.04	30.2	1.19
25.0	25.4	1.0178	2.54	37.1	1.49
30.0	30.6	1.0214	3.04	44.0	1.79
35.0	35.8	1.0250	3.54	50.7	2.10
40.0	41.1	1.0286	4.03	57.3	2.41
45.0	46.4	1.0322	4.52	63.8	2.73
50.0	51.7	1.0359	5.03	70.1	3.05
55.0	57.1	1.0395	5.51	76.3	3.36
60.0	62.5	1.0431	5.99	82.4	3.70
65.0	67.9	1.0468	6.48	88.3	4.02
70.0	73.4	1.0504	6.95	94.1	4.38
75.0	78.9	1.0541	7.44	99.8	4.70
80.0	84.5	1.0578	7.92	105.0	5.08
85.0	90.1	1.0615	8.40	110.5	5.41
90.0	95.7	1.0652	8.88	116.0	5.81
95.0	101.4	1.0689	9.35	121.0	6.16
100.0	107.1	1.0726	9.81	126.0	6.56
110.0	118.6	1.0801	10.75	136.0	7.35
120.0	130.3	1.0876	11.68	145.0	8.18
130.0	142.1	1.0952	12.60	154.0	9.04
140.0	154.1	1.1028	13.52	163.0	9.94
150.0	166.3	1.1105	14.43	171.0	10.89
160.0	178.6	1.1182	15.33	179.0	11.89
170.0	191.1	1.1260	16.23	186.0	12.94
180.0	203.7	1.1339	17.12	193.0	14.04
190.0	216.6	1.1418	18.01	199.0	15.22
200.0	229.6	1.1498	18.89	204.0	16.46
220.0	256.1	1.1660	20.64	213.0	19.18
240.0	283.3	1.1825	22.38	220.0	
260.0	311.3	1.1993	24.10	225.0	

1: Grams of anhydrous sodium chloride per kilogram of aqueous solution.
2: Grams of anhydrous sodium chloride per litre of aqueous solution.
3: Specific gravity of solution at 20 °C.
4: Density on Baumé scale (US) at 20 °C. At 20 °C, specific gravity=145/(145-°Bé).
5: Electrical conductivity at 20 °C in mS/cm.
6: Freezing point depression.

Conductivity is perhaps the most widely used surrogate measure of salinity. Sometimes, readings are not even converted to units of salinity but quoted directly as 'salinity' in units of electrical conductivity ('EC' units). The conductivity of a salt solution depends upon ionic composition, total ion concentration and temperature and must therefore be used with care as a measure of salinity. Nevertheless, in regions where salt lakes are reasonably homogeneous with regard to ionic composition, the correlation between conductivity and salinity can be quite close, as Fig. 2.1 shows. The figure illustrates the relationship in Australian salt lakes. In almost all of these, Na^+ and Cl^- are the dominant ions. The figure is based upon a large number of full ion analyses to give salinities and upon contemporaneous conductivity measurements. Between salinities of ~5 and 70 g/L, the relationship illustrated in Fig. 2.1 can be described by the equation (Williams, 1986):

$$s = 0.466K^{1.0878} \qquad (r^2 = 0.98799)$$

where s is salinity in g/L, and K is conductivity at 25 °C in mS/cm (mS = mhos; µS = µmhos). The relationship breaks down below salinities of about 5 g/L because of increased ionic heterogeneity, and above about 70 g/L because of ion antagonism. The latter can be adequately dealt with by appropriate dilution of samples. Different relationships between conductivity and salinity will obtain in salt lakes elsewhere, according to ionic composition and the degree of ionic homogeneity (or heterogeneity). Nevertheless, as a general rule, conductivity does provide a good indication of salinity for most salt lakes worldwide. Approximate temperature corrections to 25 °C can be made using the equation (Smith, 1962):

$$K_{25} = K_t/(1 + 0.025\,[t - 25])$$

where K_{25} is the conductivity at 25 °C and K_t the conductivity at temperature t °C. Many modern conductivity meters automatically correct to 25 °C. Relatively cheap and robust conductivity meters are now commercially available.

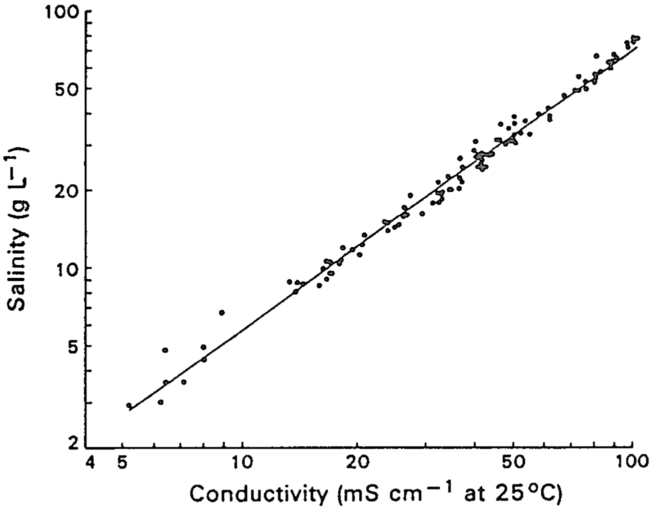

Fig. 2.1 Relationship between conductivity and salinity in Australian salt lakes. After Williams (1986a).

The determination of the extent to which temperatures at which solutions freeze are depressed (freezing point depression, Δt) is not often used by limnologists as a measure of salinity, but such values are of considerable interest to physiologists because of their relation to osmotic pressure. Table 2.1 indicates Δt for various concentrations of sodium chloride solutions.

The determination of total dissolved solids (matter) (often abbreviated as TDS or TDM) or total filterable residue (TFR) is more widely used as a measure of salinity. Water from a known volume of sample is evaporated, usually at 105 °C, and the residue dried to constant weight.

Care is needed in the use of units to express salinity. Results can be expressed on a mass per mass basis (mass of total ions per mass of solution) or on a mass per volume basis (mass of total ions per volume of solution). Units are often g/kg or parts per thousand (ppt, *‰*) for mass/mass, and g/L for mass/volume. These units are essentially interchangeable at very low salinities, as in all fresh waters, but are *not* interchangeable at high salinities. This is because the density of concentrated salt solutions diverges significantly from 1.0. The relationship is:

mass/mass = mass/vol./density

i.e. *‰* = g/L/density. Table 2.1 indicates the extent of the divergence for solutions of NaCl. It is clearly not insignificant at high salinities. For several reasons, but especially because they are temperature independent, it is best to express salinities whenever possible on a mass/mass basis. The most convenient unit to do this is g/kg (ppt). However, the preferred method is not always possible (as will be evident from this book) because many limnologists express data as g/L and density is unknown.

An important feature of many salt lakes is that salinities may change significantly in time and space: seasonal and long-term (secular) changes may occur within a lake, and salinities may be quite different in adjacent lakes and both vertically and horizontally within one lake. 'Mean' or 'modal' salinity, therefore, is a value to be treated with reservation. Bearing this in mind, however, few salt lakes have mean salinities approaching saturation values (at least for long), and modal values generally lie between 10 and 100 ppt. The explanation lies in the fact that few salt lakes are entirely closed systems hydrologically: there is a dynamic balance between salt loss and gain.

In small, shallow salt lakes, spatial differences are infrequent. The wind acts as an effective mixing agent preventing the development of any horizontal or vertical differences. In larger, deeper salt lakes, however, horizontal differences may occur, such as those in the Aral Sea, where salinities are lower near inflows, and in the two basins of Lake Balkhash, which are separated by a shallow sill. They also occur in solar salt pond series, with the salinity of ponds near marine inputs being near 35 ppt, and that of ponds near the end of the series (crystallizing or evaporating ponds) being near 300 ppt. Despite these examples and others, marked horizontal differences in salinity are not a common feature of salt lakes whatever their size.

Of more frequent development than horizontal differences, though by no means common, are vertical differences in salinity in deep salt lakes. General patterns involve an upper layer of less saline water (the mixolimnion) within which water circulates but which does not mix with a lower layer of more saline water. The two layers are separated by a chemocline or chemolimnion. Lakes so stratified are termed meromictic lakes and in them significant vertical differences in temperature, oxygen concentration and many other features are associated with the salinity differences. Meromictic conditions are usually long-lived (indeed, the term meromixis was originally coined to refer to long-continued stratification of both freshwater and saline lakes) but may occasionally be of seasonal occurrence. When a long-lived meromixis breaks down, the event is often notable, as in the Dead Sea where meromixis broke down recently (1979) after a period of several hundred years of meromictic stability. Two types of phenomena have been identified as causative agents for meromixis: those external to the lake (ectogenic), such as subsurface or surface inflows of fresh or saline water, and those internal to the lake (endogenic), such as the incomplete solution of salt deposits and salt 'freeze-out'.

Several patterns of salinity fluctuation in time occur. In large, permanent salt lakes, salinity may be more or less constant over long periods and change naturally only in response to regional shifts in climate. Many recent changes in the salinity of such lakes -almost always in an upward direction- are the result of human diversion of inflow waters, as will be discussed later. In other, smaller permanent salt lakes, fluctuations may show dampened seasonal patterns. Temporary salt lakes, on the other hand, are characterized by pronounced salinity fluctuations. In intermittent salt lakes, these are seasonal, with low salinities usually found shortly (but not immediately) after major inflows have taken place, and high salinities shortly before the lake dries. This type of pattern is displayed in Fig. 2.2 which shows monthly salinity in an intermittent salt lake in south-eastern Australia over several years. In episodic salt lakes, salinities are also lowest shortly after filling (though they may be very high *immediately* after filling as salt crusts dissolve). They increase as the lake dries but this may take from a few weeks for small episodic lakes to over a year for large examples (Fig. 2.3).

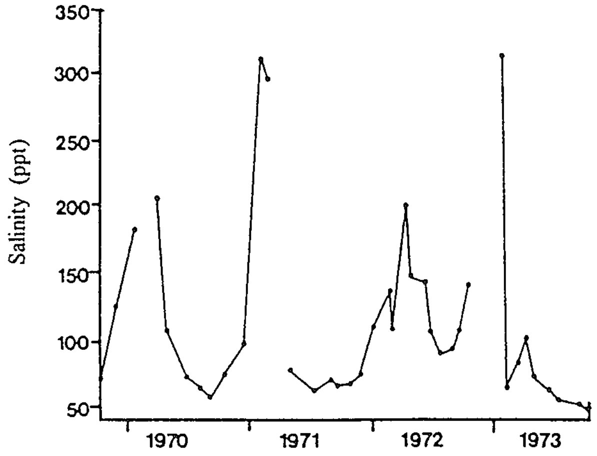

Fig. 2.2 Salinity in Lake Eurack, Victoria, Australia, 1970-1973. Gaps in record indicate periods when lake was dry. After Williams (1984).

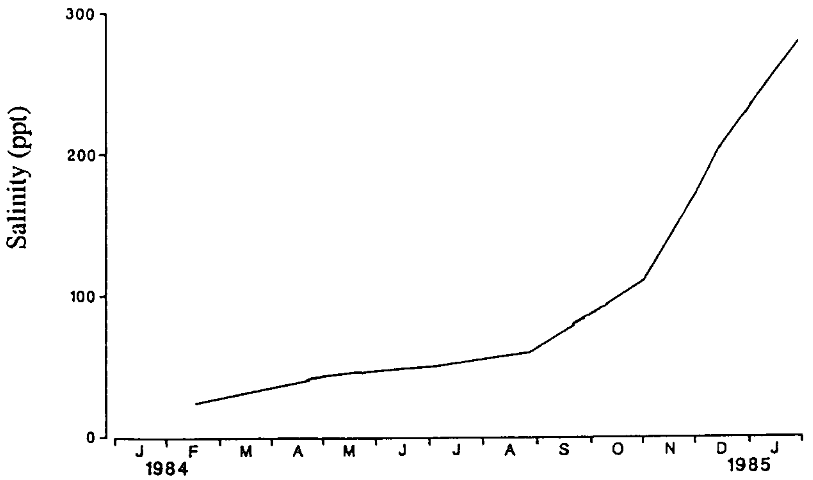

Fig. 2.3 Salinity in Lake Eyre North, Australia, during a recent filling. After Williams (1990).

2.2 CHEMICAL COMPOSITION

The major ions comprising the salinity of salt lakes are, as previously mentioned, essentially those of fresh waters: monovalent cations are Na^+ and K^+, divalent ones, Ca^{2+} and Mg^{2+}, and anions are Cl^-, SO_4^{2-}, HCO_3^- and CO_3^-. Occasionally, other ions normally found in trace amounts are found in significant concentrations, e.g. borates in Borax Lake, California, and bromides in the Dead Sea. Whilst the same major ions are found as in fresh waters, the proportions are usually different in salt lakes. In most fresh waters, it is the divalent cations and carbonates that are important, whereas such combinations are not characteristic of saline waters. Table 2.2 indicates a little of the variety of ionic compositions encountered in saline lakes. It documents the ionic composition of some important and well-known salt lakes from various continents using both absolute (g/L) and relative concentrations (equivalent percentage). Relative ionic proportions in salt lakes are often displayed in the form of ternary diagrams. Figure 2.4 does this for the data of Table 2.2. Ternary diagrams of this sort enable easy visual recognition of different ionic compositions (but generally not total ion concentrations, although sometimes attempts to do this roughly are made by making symbols of different sizes, each size indicative of a salinity size class).

Table 2.2 Major ion composition of some important saline lakes. The data have been selected to illustrate both chemical variety and the chemical nature of particular salt lakes. Data for seawater are included for comparative purposes. A, values as g/L; B, values as percentage equivalents of cations or anions. After various sources (note: significant changes in salinity and composition may have occurred since the original analyses).

Lake	Value	Salinity	Na	K	Mg	Ca	Cl	SO_4	HCO_3	CO_3
Redberry	A	18	1.9	0.2	2.3	0.1	0.2	12.5	0.6	0.1
(Canada)	B		29.2	1.7	67.4	1.8	2.2	93.1	3.2	1.5
Van (Turkey)	A	23	8.1	0.4	0.1	0.0	5.9	2.4	2.4	3.5
	B		94.8	2.8	2.4	0.1	44.6	13.6	10.7	31.1
Seawater	A	35	10.8	0.4	1.3	0.4	19.4	2.7	0.1	0.0
	B		77.0	2.0	18.0	4.0	90.0	9.3	0.4	0.0
Bogoria (Kenya)	A	36	14.4	0.3	0.0	0.0	3.4	0.2	(17.7)	
	B		98.6	1.2	0.0	0.2	14.1	0.6	(85.3)	
Gallocanta	A	40	7.9	0.2	3.4	0.3	18.1	9.7	0.0	0.1
(Spain)	B		53.1	1.0	43.3	2.6	71.3	28.3	0.0	0.3
Soda (USA)	A	82	20.0	1.5	3.4	0.6	4.1	50.4	1.5	0.8
	B		71.4	3.2	22.7	2.6	9.5	86.2	2.0	2.3
Mono (USA)	A	89	29.5	1.5	0.0	0.0	17.6	10.3	11.2	18.9
	B		96.9	2.9	0.2	0.0	32.6	14.1	12.0	41.3
Eyre North	A	116	45.8	0.0	0.3	0.9	68.0	2.9	0.0	0.0
(Australia)	B		96.4	0.0	1.3	2.3	95.9	4.1	0.0	0.0
Dead Sea, surface	A	295	38.5	6.5	36.1	16.4	196.9	20.6	0.2	0.0
(Israel/Jordan)	B		29.7	2.9	52.8	14.5	98.7	0.2	0.1	0.0
Great Salt Lake,	A	332	105.4	6.7	11.1	0.3	181.0	27.0	0.5	0.3
North (USA)	B		80.6	3.0	16.0	0.3	89.8	9.9	0.2	0.2
Don Juan	A	339	11.5	0.2	1.2	114.0	212.0	0.0	0.0	0.0
(Antarctica)	B		7.9	0.7	1.6	90.4	100.0	0.0	0.0	0.0

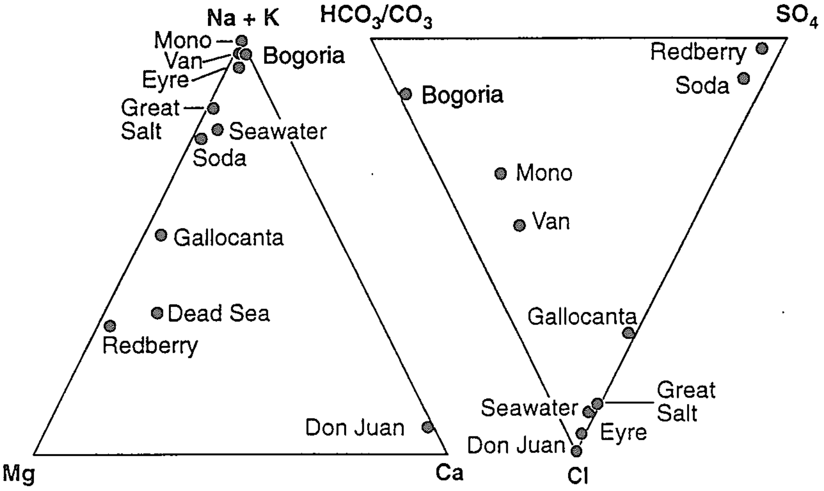

Fig. 2.4 Ternary diagrams to illustrate ionic composition of lakes listed in Table 2.2. Apices indicate 100 equivalent percentage of cations or anions.

Despite the variety of ion compositions shown in Table 2.2 and Fig. 2.4, certain combinations of ions are more frequently encountered than others (and some never). Na^+ is easily the most common cation found, and Cl^-, the most common anion (though SO_4^{2-} and HCO_3^- or CO_3^{2-} are not rare by any means). Five ion combinations are generally encountered:

Major cation	Major anion(s)
Na	Cl
Na	$Cl > CO_3$
Na	$Cl > SO_4$
Na	$HCO_3 + CO_3$
Na	$HCO_3 + CO_3 > Cl$

Salt lakes, as a result, are often typified chemically as chloride, chlorocarbonate, chlorosulphate, carbonate or carbonate-chloride lakes. These frequently show regional distributions, so that in East Africa, for example, many lakes are sodium carbonate/carbonate-chloride lakes, whereas in Australia, almost all lakes are sodium chloride lakes.

Like salinities, ionic proportions may change in time and space and such changes, not surprizingly, usually correlate with salinity. Thus, spatial changes in ionic proportions may occur near inflows, in solar salt pond series, and in meromictic lakes. Temporal differences may develop as the maximum solubility of certain ion combinations (salts) is exceeded and precipitation occurs, or, over much longer periods, as brines 'evolve' in accord with the composition of inflow waters. The composition of these, in turn, is determined by the nature of the sources of the ions - of which there are several, including cyclic salts (essentially, marine-derived salts accessed from precipitation or dry atmospheric fall-out), geological deposits, rock leaching, hydrothermal sources and relictual sea-water.

Notwithstanding the occurrence of some spatial and temporal changes in ionic composition, marked changes in major ionic composition within a lake, both in space and time, are not usual: within the water mass of most lakes, and both seasonally and over longer time spans, most salt lakes remain relatively stable so far as major ionic proportions and composition are concerned. Several explanations are involved. In permanent salt lakes, salinities may not change much and as a consequence nor do ionic proportions. If they do change, the extent may be insignificant so far as salt solubilities are concerned. And salt lakes with marked salinity fluctuations (temporary salt lakes) usually do not act as sealed basins in which brines and precipitated salts remain chemically isolated from interstitial pore water in sediments and groundwater; usually, interchange between the water and salts in all three compartments takes place so that the final water on the surface of a temporary salt lake about to dry is more to be regarded as the last visible surface 'lens' of a larger subsurface water-body. Winter (1995) gives a modern and comprehensive account of hydrological processes and the water budget of lakes.

Of course, in lakes where the sediments act as an effective hydrological seal, changes in ionic proportions are to be expected. For those lakes with an initial composition not unlike sea-water, the order of salt precipitation is $CaCO_3$ (calcite, aragonite), $CaSO_4$ (gypsum), NaCl (halite) and $KCl/MgCl_2$ (potash, etc). This is the sequence which occurs in solar salt ponds and the data shown in Table 5.1 (based on results observed as sea-water evaporated in the laboratory; see also Fig. 5.3) are used by solar pond operators as a guide in their management.

Many other minerals precipitate from salt lakes. The nature of these is in accord with the ionic composition of the initial solution, concentrations of dissolved organic matter, and physical (climatic) and other conditions. Lake sediments where minerals have accumulated in large amounts are referred to as *evaporites*. The composition of these may change after primary deposition and their study is a complex and - given the large economic value of many evaporites (see chapter 4) - an important branch of geochemistry. Sonnenfeld (1984) is an important reference text in this area of salt lake studies.

With regard to minor ions, the concentrations of the major plant nutrients (ammonium salts, nitrates and nitrites, phosphorus) recorded from salt lakes span a wide range of values.

Early opinions concerning phosphorus were that high levels were generally characteristic, but while high levels have indeed been recorded from many salt lakes, some salt lakes (like many in Antarctica) are very deficient in dissolved phosphorus. Some very high values include one of 300 mg/L from Lake Nakuru in Kenya. Most values recorded are very much smaller, but even so it appears that phosphorus is not usually a limiting factor in most salt lakes. Interactions between salinity and phosphate concentrations are complex and one suggestion is that at least in certain temporary salt lakes seasonal changes in dissolved phosphate may be linked to seasonal cycles in salinity and adsorption-desorption processes in sediments. In meromictic lakes, the lower layer (monimolimnion) may act as a phosphate sink. At a practical level, note that high salinity may lead to underestimation of phosphate levels when the commonly used molybdate analytical technique is employed (Sherwood et al., 1995).

Concentrations of the various forms of nitrogen in salt lakes, like those for phosphorus, span a wide range of values and interactions with salinity are complex (Ghassemzadeh et al., 1997). An additional complication is that many blue-green algae and other bacteria characteristic of salt lakes, e.g. *Nodularia spumigena*, have the ability to fix dissolved gaseous nitrogen. Even so, where phosphorus is not a limiting plant nutrient, available forms of nitrogen have been implicated as limiting nutrients for plant growth.

The concentration of plant nutrients in natural salt lakes is not as important an issue as it is in many freshwater lakes where problems of eutrophication frequently intrude as an issue of water management. There is no doubt, however, that salt lakes which receive sewage and other effluents with high concentrations of plant nutrients do not escape eutrophication, a situation compounded by the frequent use (and inapplicability) of loading factors derived from and intended for use with open freshwater systems (Williams, 1981). The concentration of plant nutrients in solar salt ponds is often an important management issue in terms of ultimate effects on the quality and quantity of salt harvested. Both too few and too many plant nutrients can lead to problems (Davis, 1978, 1991). The balance between phytoplankton and microbial mat development in solar salt ponds is often significant. Microbial mats - frequently dominated by *Aphanothece (Coccochloris)* - are important in some ponds because they seal the pond bottom, but overproduction of some of their constituent species may lead to undesirably high brine viscosities and algal mucilage and consequential problems in salt harvesting, to poor quality salt, or to other problems (Roux, 1996; Ghassemzadeh et al., in press). Excessive phytoplankton densities may inhibit the development of microbial mats and effect evaporation rates. The question of nutrient inputs and the effect on salt quality and quantity in salt ponds is particularly important where salt ponds draw on seawater contaminated by sewage effluent.

For other dissolved inorganic substances present in small concentrations in salt lakes, little need - or in many cases can - be written here. Note, however, that because of their closed nature many salt lakes act as much more effective chemical sinks than do fresh waters, and this may lead to problems when the concentrations of heavy metals, persistent pesticides and other noxious substances build up. Problems associated with the evaporative accumulation of boron, arsenic, selenium, molybdenum and uranium in salt evaporation ponds in California have already arisen, including especially the problem of their impact on waterfowl (see section 5.4).

Dissolved organic matter (DOM) in salt lakes is beginning to emerge as an important chemical component that may have been undervalued in terms of biological significance (see Thomas, 1997). Some high concentrations have been reported and Javor (1989) has suggested that hydrocarbons accumulate in salt lakes because they are recalcitrant to oxidation by halophilic microorganisms. Perhaps the known association of petroleum deposits with evaporites (Kirkland and Evans, 1981) results from the accumulation of DOM in salt lakes.

2.3 pH

A wide range of pH values is encountered in saline lakes. Perhaps most salt lakes have values >7.0, but there are some, especially in certain parts of Australia, where values are exceedingly low, in some cases as low as 3.0 (e.g. in Lake Gillies, South Australia). The biodiversity of these is very low; presumably, few species have been able to adapt to both high salinity *and* low pH. Conversely, values as high as 11.0 have been recorded from salt lakes in Kenya, North America and elsewhere, especially where Na and HCO_3/CO_3 are the dominant ions. Their biodiversity is much higher than that of acid salt lakes.

Values for pH are often variable, being determined for example by diel changes in photosynthetic rates. The relationship between pH and other chemical factors is in any event highly complex. As a general rule, however, pH and alkalinity are linked such that as alkalinity increases so does pH. In solar salt ponds, pH increases as salinity increases up to ~50 ppt (when pH is about 9.0), after which it decreases with further concentration. In many natural salt lakes, on the other hand, as salinity increases so may pH (but note that the reverse may also happen).

2.4 OXYGEN

The solubility of oxygen in water decreases significantly as the salinity of the water increases. The solubility, however, depends not only on salinity *per se* but also on the chemical nature of the water in question (as well as temperature and altitude). For this reason it is not possible to provide a simple table of equilibrium oxygen concentrations at various salinities and temperatures (of the sort available for fresh waters). Nevertheless, since most salt lakes are dominated by Na and Cl ions, values which apply to various concentrations of NaCl are often broadly applicable. Table 2.3 provides details for selected concentrations of NaCl at various temperatures. Note that at concentrations of <3 ppt (i.e. fresh waters) and at 0 °C the equilibrium concentration of oxygen is about 14 mg/L; at the same temperature, this concentration drops to only 2 mg/L at 260 ppt. Even smaller concentrations of oxygen are found at higher temperatures. At a temperature of 20 °C and a concentration of <3 ppt, the equilibrium concentration of oxygen is about 9 mg/L, and at the same temperature but at a concentration of 260 ppt this concentration is <2 mg/L. Concentrations as small as those found at high salinities may be critically limiting for the biota.

Table 2.3 Predicted equilibrium concentration of oxygen (mg/L) as a function of NaCl concentration and temperature. Extracted from Sherwood et al., (1972)

NaCl concentration (ppt)	Temperature(°C)						
	0	5	10	15	20	25	30
0	14.60	12.79	11.34	10.13	9.10	8.22	7.49
2	14.40	12.63	11.2	10.01	9.00	8.13	7.42
5	14.12	12.39	11.00	9.84	8.85	8.00	7.30
10	13.65	11.99	10.66	9.55	8.60	7.79	7.12
15	13.20	11.61	10.34	9.27	8.36	7.58	6.93
25	12.33	10.88	9.72	8.74	7.90	7.18	6.58
50	10.37	9.22	8.29	7.50	6.82	6.24	5.75
100	7.24	6.53	5.95	5.46	5.03	4.65	4.33
150	4.96	4.54	4.20	3.90	3.64	3.40	3.21
200	3.34	3.10	2.91	2.74	2.58	2.45	2.33
260	2.03	1.92	1.83	1.75	1.67	1.61	1.55

2.5 MORPHOMETRY

Salt lakes range in size from the world's largest lake, the Caspian (429,000 km^2), to small bodies of shallow water of <1 km^2 area. Some important morphometric parameters of those lakes which exceed 500 km^2 in area are given in Table 2.4. As the table indicates, some large salt lakes are quite deep, whereas others, despite their large area, are relatively shallow. The same situation prevails for small salt lakes, with some relatively deep, others quite shallow. Morphometry reflects lake origins so that as a general rule the deepest salt lakes are of tectonic or volcanic origin and the shallowest, of solution or aeolian origin.

Table 2.4 Major morphometric parameters of some important salt lakes >500 km^2 in area. After various sources (but note: predictably, data from different authors often do not exactly correspond; data are best estimates).

Lake	Area ($km^2 10^3$)	Volume (km^3)	Mean depth (m)	Maximum depth (m)
Caspian	429.1	78,000	187	960
Aral[1]	68.0	1,090	16	69
Balkhash	22.0	122	6	27
Eyre, North[2]	7.7	23	3	6
Issyk-kul	6.3	1,730	275	702
Urmia	6.0	29	5	
Qinghai	4.6	85	19	29
Great Salt Lake	4.4	19	4	10
Van	3.6	191	53	77
Dead Sea	0.9	136	145	330

1. For period pre-1960.
2. Lake Eyre is an episodic lake. The data relate to the time the lake is full.

2.6 WATER-LEVELS

Morphometric features of most salt lakes are a great deal more variable than they are in most freshwater lakes. This reflects the greater hydrological sensitivity of salt lakes to seasonal and secular changes in climate. The actual patterns of variability relate to lake basin morphology, geographical location and the nature of climatic changes. The most obvious manifestations are fluctuations in water-level and water permanency. Several patterns may be discerned. They accord with patterns of fluctuation in salinity already discussed (see above). Thus, in large, deep salt lakes water is permanently present and little if any natural change in water-levels may take place over long periods. When changes in water-level do occur, they reflect regional climatic shifts. In smaller and less deep salt lakes, water may still be present permanently but levels may show dampened seasonal fluctuations in addition to secular changes. Shallow salt lakes frequently lose all surface water. In arid regions, where rainfall occurs more or less unpredictably and lakes are episodic, water may be present in small lakes for only a short period after filling (<1 month), but persist for over a year in very large lakes. For example, it takes over one year for water to evaporate or seep from Lake Eyre, a large shallow lake in central Australia, when this lake is infrequently filled. Smaller lakes in the same region retain water for much shorter periods. In less arid regions, where rain falls in a more or less seasonally predictable fashion, shallow salt lakes contain water in a regular seasonal pattern.

The sensitivity of salt lake morphometry to inputs of water (as well as to other elements of the hydrological budget) has resulted in significant changes to the water-levels of salt lakes wherever inputs are subject to human impact. The most obvious impact involves diversions of water from inflowing streams and rivers for irrigation and other purposes. This impact is discussed in more detail later with respect to particular lakes (chapter 6) and all that need be noted here is that many large salt lakes throughout the world have experienced significant falls in water-level (and consequential rises in salinity) over the past few decades as water is diverted from them (Williams, 1993b, 1996b). A single example will suffice to make the point here. The water-level of the Aral Sea, a very large salt lake in central Asia, has dropped some 15 m since 1960 and its salinity has risen from 10 to 30 ppt in the same time period as waters from the Amu- and Syr-darya have been progressively diverted for irrigation (see section 6.2 and Fig. 6.4).

For shallow and smaller salt lakes, additional impacts include increasing degrees of desiccation as nearby groundwater is pumped for human use (as in many salt lakes in Mexico; Alcocer and Escobar, 1990). Mexico City is sinking at a mean rate of 30 cm a year because of this phenomenon (Alcocer and Williams, 1996). Changes to hydrological patterns following alteration to runoff characteristics when catchments have their natural vegetation removed, are over-grazed, or become eroded are also involved.

2.7 LIGHT

Deep salt lakes are usually clear and light can penetrate many metres. In many shallow salt lakes, on the other hand, light can often penetrate no more than a few centimetres because of numerous particles suspended in the water column. These particles may be of biological origin (e.g. phytoplankton), but more often are inorganic materials derived from sediments or, in a few cases, inflowing streams. Considerable fluctuation (perhaps, even, volatility) in the extent of light penetration in shallow salt lakes appears to be the general rule because the amount of suspended material is closely related to wind strength: in windy conditions, high turbidity prevails; in calm conditions, light reaches the lake bottom. Seasonal patterns obviously occur.

Apart from decreasing the extent to which light may penetrate the water column, suspended material may also impart a distinctive colour to the lake. Dense blooms of blue-green algae often result in deep green lakes. When large populations of Halobacteria or *Dunaliella*, a green alga, are present, lakes appear red or pink (hence the reason for so many salt lakes called 'Pink Lake') (Oren et al., 1992). Large amounts of suspended clay or other inorganic particles result in water coloured white or light grey. In the absence of large amounts of suspended particles but the presence of significant amounts of dissolved organic matter, lake waters may appear brown. A thorough comparative study of how spectral quality varies with depth and what determines this variation in salt lakes has yet to be made. Note only that considerable variation occurs between lakes.

2.8 THERMAL CHARACTERISTICS

A variety of thermal patterns of mixing and stratification occurs in salt lakes. Because of wind action, moderately shallow salt lakes are usually polymictic, that is, frequently stratify into an upper, warmer layer (epilimnion) and a lower, colder layer (hypolimnion) and, as frequently, lose this stratification. Very shallow salt lakes in exposed situations may never stratify, but even in these on calm days surface waters may be significantly warmer than deeper waters given that the longer wavelengths of the spectrum (those imparting most heat) are rapidly absorbed in water. Absorption of this part of the spectrum is about 10 to 100 times greater than the photosynthetically important parts of the spectrum. Usually in very shallow salt lakes there are no vertical differences in temperature.

Deep salt lakes stratify on a seasonal basis as a general rule. For those in warm semi-arid regions, the warm monomictic pattern is characteristic: the lakes stratify thermally during the warmer season and mix during other seasons. Lake Gnotuk, a deep salt lake in south-eastern Australia, provides an example (Fig. 2.5). In cold regions, when ice forms during winter, dimictic patterns occur.

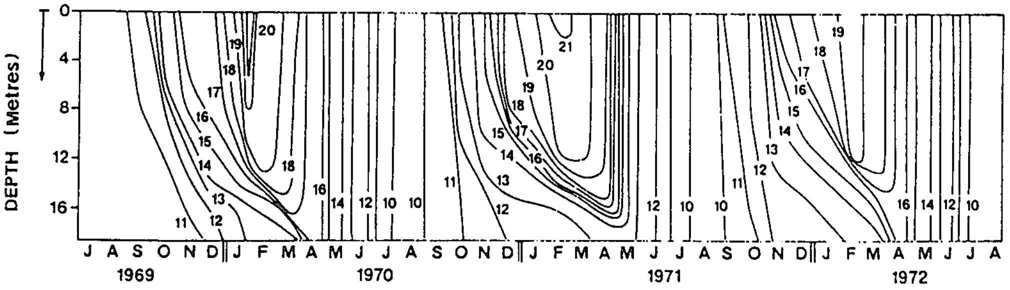

Fig. 2.5 Pattern of thermal stratification in Lake Gnotuk, Victoria. After Timms (1976).

Salinity is an important factor in determining thermal patterns and the depths of epi- and hypolimnia, when these develop, since salinity and density are related. Thus, a given amount of wind energy will mix water in a salt lake to a shallower depth than is the case in a freshwater lake. And, of course, the higher the salinity, the shallower the depth of the mixing zone. Salinity is also important in that dissolved salts in water depress the temperature at which the water freezes: the higher the salinity, the lower the temperature at which surface ice will form.

Again, salinity is important in the particularly interesting thermal pattern found in meromictic salt lakes, that is, salt lakes in which there is an upper layer of less saline water and a lower one of more saline water. The phenomenon has been discussed above in relation to the development of vertical differences in salinity within lakes. Associated with this chemical stratification is an inverse thermal stratification: patterns are often complex and display seasonal variation but in simple terms the upper layer (mixolimnion) is colder than the lower one (monimolimnion). Meromixis may be a more or less permanent feature and be destroyed only by unusual events. The design of so-called heliothermal ponds is based on meromictic lakes and in the monimolimnia of these ponds temperatures may reach 70 °C. In both heliothermal ponds and meromictic lakes the same basic physical principles operate: heat from incoming radiation is trapped in the monimolimnion and heats it up.

CHAPTER 3

BIOLOGICAL FEATURES

3.1 INTRODUCTION

In biological terms, salt lakes are commonly regarded as extreme habitats of low biodiversity, quite different in nature from other inland waters. There is some truth in this, but the statement needs to be placed in perspective to be appreciated properly. First, it must be remembered that the biota, having fully adapted to conditions in salt lakes, are not then subject to 'extreme' conditions: indeed, for them, conditions outside salt lakes are extreme. Put more generally, conditions for any species beyond those in which it presently lives are likely to be extreme. Second, whilst biodiversity in salt lakes is less than that usually found in fresh waters, a wide variety and large numbers of species are to be found in salt lakes, particularly those of low salinity. And third, all the basic ecological processes characteristic of ecosystems (production, decomposition, nutrient cycling...) occur in salt lakes. If salt lakes are different from other aquatic ecosystems, the difference is merely one of degree, not fundamental nature. In this respect, rivers and streams are no less different from freshwater lakes than are salt lakes!

Whatever the case, the biological features of salt lakes provide much for discussion. In the present context, discussion is confined to brief comments on the following topics: the composition of the biota, the extent of diversity, the nature of adaptation to environmental conditions, and salt lakes as ecosystems.

3.2 THE COMPOSITION OF THE BIOTA

Almost all (but not all) of the groups characteristically found in fresh waters are also to be found in salt lakes. Of course, species, genera and sometimes families are not the same, but, overall, the biota of salt lakes is not grossly dissimilar in composition to that of fresh waters; with some few exceptions, representatives of most groups found in fresh waters have also been found in salt lakes, and, conversely, no group found in salt lakes lacks representatives in other sorts of aquatic environment. The groups found in salt lakes are considered below on the broadest of possible bases.

The bacteria include both groups commonly and jointly referred to as bacteria (but which are not at all related): the Archaeobacteria and the Eubacteria (including the Cyanobacteria, generally if imprecisely referred to as the blue-green algae).

Archaeobacteria occur in habitats that many other living organisms have failed to adapt to and are characteristic in particular of highly saline and hot environments (e.g. hot springs). In saline environments, only two genera were recognized until recently, but currently at least six are known: *Halobacterium* (3 species), *Haloferax* (3), *Haloarcula* (2), *Halococcus* (1), *Natrobacterium* (3) and *Natronococcus* (1). Collectively, these species are often referred to as the 'halobacteria'. Most of the organotrophic bacteria of salt lakes are Archaeobacteria. They acquire carbon and energy from organic compounds (mostly amino and organic acids) and usually require oxygen to do so. A few forms use other sources of carbon and can grow in the absence of oxygen. All require high amounts of sodium. Certain species, with the aid of the pigment bacteriorhodopsin, use light for metabolic purposes. This pigment absorbs light energy at the green end of the spectrum. Additionally, halobacteria often contain high amounts of carotenoid pigments (primarily bacterioruberins) which impart a red or orange colour to waters with dense populations of halobacteria.

A variety of Eubacteria also occurs in salt lakes. The most important are phototrophic forms (use light as a source of energy) comprising the purple and green bacteria and the Cyanobacteria. Many halotolerant Eubacteria that are not phototrophic also occur.

Several genera of purple and green bacteria are found. All use various forms of bacteriochlorophyll as the pigment to absorb light energy and all grow in the absence of oxygen (are anaerobes). Some, however, are able to grow in the dark, deriving energy from organic substances, but then usually require oxygen. Amongst the best known genera are *Rhodospirillum* (a non-sulphur purple bacterium), *Chromatium* and *Ectothiorhodospira* (both purple sulphur bacteria), and *Prosthecochloris* (a green bacterium).

Many genera of the blue-green algae (Cyanobacteria) are found in salt lakes, and their species are often major elements of ecosystem processes as key components of energy pathways (e.g. as photosynthetic organisms) and biogeochemical cycles (e.g. as organisms which can convert gaseous nitrogen into more available forms of nitrogen). They occur in both the water column as phytoplankton and on bottom sediments as key elements in microbial mats (Fig. 3.1). Cohen and Rosenberg (1989) is an important reference to such mats. Few if any blue-green algae are as tolerant to salinity as the halobacteria, but certain species can tolerate salinities well above 100 ppt. Several are of considerable interest economically because of their high protein content, e.g. *Aphanothece* and *Spirulina* (Fig. 3.2a); others cause management problems, e.g. the development of noxious blooms and decreases in the quality and quantity of salt harvested from solar salt ponds. Important genera include *Aphanothece, Spirulina, Oscillatoria, Microcoleus, Dactylococcopsis* and *Nodularia. Nodularia spumigena* was implicated in the first recorded phytoplankton bloom giving rise to noxious conditions.

In any discussion, however brief, of the bacteria of salt lakes, mention should be made of so-called stromatolites. These are fossil or living structures comprising an assemblage of bacteria (as microbial mats) and sediment. Often laminated, they are amongst the oldest known fossils of organisms (some are about 3,000 million years old) and appear to have been confined to coastal marine waters and salt lakes. Stromatolite-like structures are known from several modern salt lakes (as well as coastal localities), although it has been suggested that the term stromatolite is best restricted to fossil structures and that other terms be used for modern growths. The biological elements of the oldest fossil stromatolites were purple and green bacteria, but modern structures for the most part involve the Cyanobacteria.

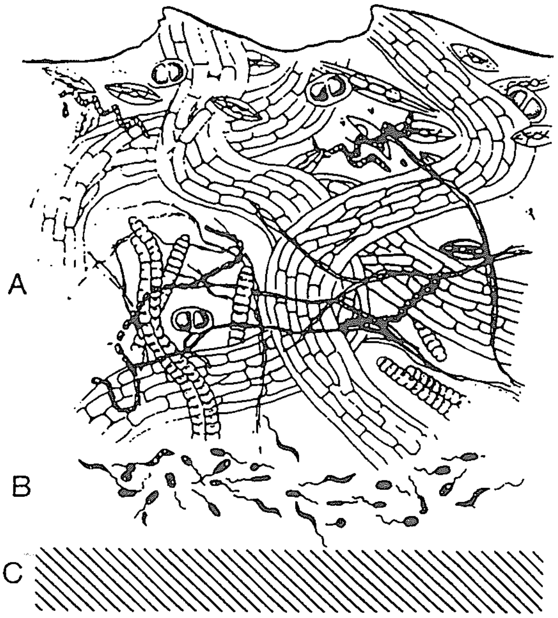

Fig. 3.1 Schematic representation of a vertical section through a summer microbial mat from the Salada de Chiprana, Spain. The individual taxa are not named. A, green layer; B, red layer; C, sediments. After Guerrero et al., (1991).

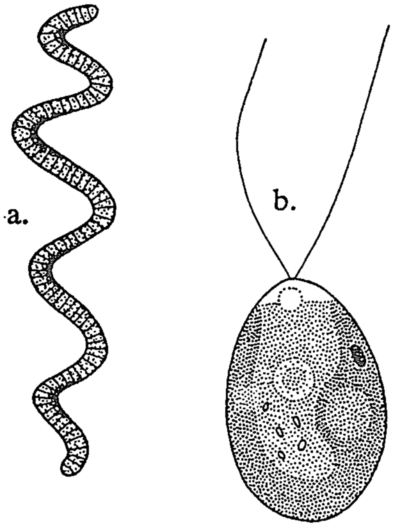

Fig. 3.2 a, *Spirulina* a blue-green alga; b, *Dunaliella*, a green alga. After various sources.

With regard to true algae, all major groups found in fresh waters also occur in saline lakes. Microscopic forms, the majority, occur either in the water column (as phytoplankton) or on the bottom of the lake as algal mats. A few large forms are found attached to bottom sediments. The greatest number of species has been recorded from hyposaline lakes (salinity, 3-20 ppt), but large numbers are known from mesosaline lakes (20-50). Numbers are relatively restricted at salinities >50 ppt (hypersaline lakes), but even so all major groups are also represented in highly saline lakes. *Amphora, Navicula,* and *Nitzschia* are amongst the most frequently encountered diatoms (Bacillariophyta) found in hypo- to mesosaline lakes. Exceedingly high tolerances to salinity are displayed by some species of Chlorophyta. The most tolerant and important of these is *Dunaliella salina* (Fig. 3.2b). It is important because it is often the only and certainly always the most significant photosynthetic organism found in highly saline lakes (its range of salinity tolerance is ~20-350 ppt), it is of economic interest as a source of carotenoids (see chapter 4), and it is of considerable scientific interest (Avron and Ben-Amotz, 1992). A small, unicellular and motile species, its cells accumulate carotenoids at high salinities and, like the halobacteria, dense populations impart a red colour to water containing them. Found throughout the world, it reproduces both sexually and asexually and has several growth forms. *Dunaliella salina* is not the only species in the genus, but disagreements have existed over the exact limits to species.

Other chlorophytes found in salt lakes and of particular interest include *Botryococcus braunii*, which has high intracellular concentrations of oils, *Enteromorpha intestinalis*, a macroscopic filamentous form, and *Ctenocladius* (also a macroscopic filamentous form), a widespread if not cosmopolitan form tolerant of salinities to 200+ ppt. Macroscopic algae found in salt lakes usually belong to the Charophyta. Important forms are *Tolypella* and *Chara* at moderate salinities (<50 ppt), and *Lamprothamnium papulosum* at salinities up to ~150 ppt.

Finally, with respect to algae, brief mention should be made of *Prymnesium parvum*, a haptophyte. A euryhaline form growing at salinities from <3 to ~33 ppt, it is of management interest because under certain conditions it becomes toxic to fish.

For many reasons, but especially because of salinity intolerance and fluctuating water levels, the diversity of higher plants (macrophytes) found either partially or totally immersed in salt lakes is not high. Most are restricted to hypo- and mesosaline lakes where they are represented by halotolerant forms such as *Potamogeton pectinatus* and *Phragmites australis*, both widespread species. These are rooted species found in marginal situations, the former, totally submerged, the latter, an emergent species. A few forms are more tolerant. Some of the most tolerant have been found in Australia and special mention is made of species of *Lepilaena* and *Ruppia* in this context (Brock, 1997). Both genera have species which can be found alive and totally submerged at salinities well above 100 ppt. *Scirpus maritimus*, an emergent North American species, is also quite halotolerant and has been found in hypersaline lakes (~60 ppt).

A greater variety of halotolerant angiosperms are found growing beyond the water's edge (although sometimes inundated) on saline soils. Many of these also grow in saline conditions not associated directly with saline lakes or in coastal situations. Most belong to the family Chenopodiaceae, a cosmopolitan family containing over 500 genera and 1,500 species, most of which are small bushes. Genera frequently found around the margins of salt lakes include *Sueda, Sarcocornia* and *Halosarcia* (Fig. 3.3). They possess many species. Also on saline soils bordering salt lakes are some trees whose roots are clearly able to function in saline conditions. Tamarisks (*Tamarix hispida*), casuarina (especially *Casuarina equisefolia*), mesquites (especially *Prosopis tamarugo*) and certain ti-trees (*Melaleuca halmaturorum*) are some known to be particularly halotolerant. None is cosmopolitan, though many have been spread widely by man.

Finally, note that a few aquatic fungi have been recorded from salt lakes but that they do not seem to be an important component of the biota.

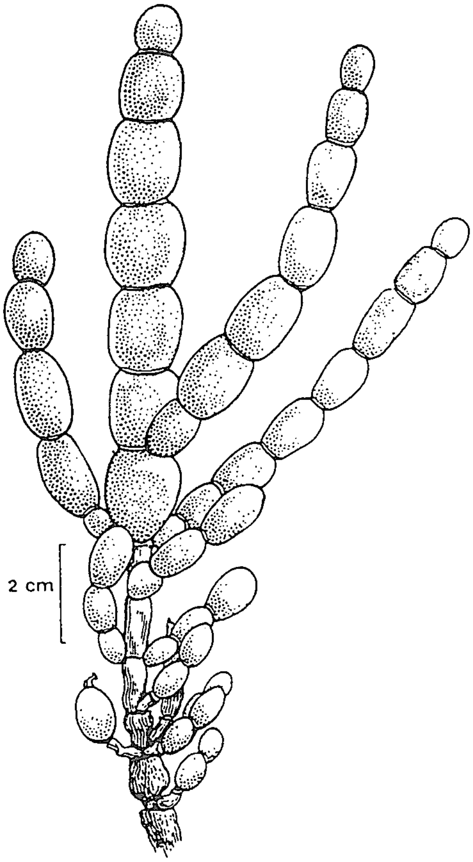

Fig. 3.3 *Halosarcia*, a macrophyte (chenopod) which grows in saline terrestrial situations.

The most conspicuous invertebrate animals are crustaceans, but many representatives of the Protozoa, particularly ciliates but including also other sorts of protozoan, and the Rotifera, though less conspicuous, are frequently encountered. Indeed, one of the most common and cosmopolitan species of salt lakes is the rotifer *Brachionus plicatilis* (Fig. 3.4). A wide variety of other non-crustacean groups also occur.

Of crustaceans, by far the best known is *Artemia*, the brine shrimp (Fig. 3.5). At one time it was thought that a single worldwide species existed, '*A. salina*'. It is now known that the genus is a complex of species and superspecies defined largely, though not entirely, by the criterion of reproductive isolation. Bisexual species include some seven species, some considerably restricted geographically, whereas parthenogenetic forms are all placed, not entirely satisfactorily, within a single species, *A. parthenogenetica*. Without supporting evidence from cytogenetics, allozyme and DNA analyses, cross-breeding and fertility trials, and morphological studies of the adults, cysts and nauplii, all material of *Artemia* should be referred to simply as *Artemia* sp. Browne and Bowen (1991) actively discouraged the use of the name *A. salina*. Note that introductions further complicate determining the identity of species.

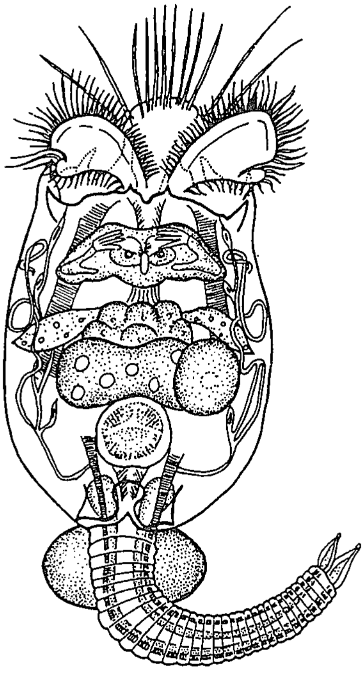

Fig. 3.4 *Brachionus plicatilis*. A cosmopolitan rotifer. After Walker (1981).

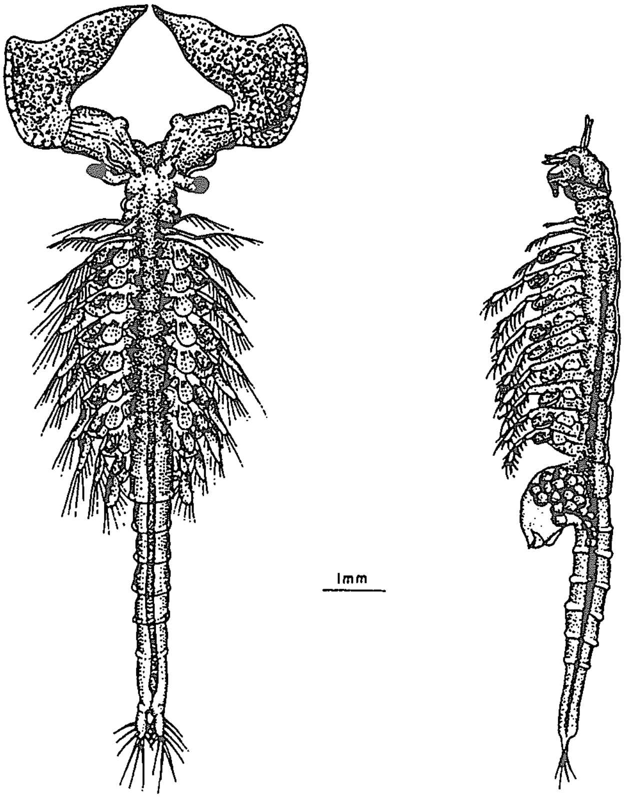

Fig. 3.5 *Artemia* sp. Left, male; right, female. After Geddes (1981).

A good deal is known about the biology of *Artemia*, not least because of its importance in aquaculture (see chapter 4). Browne, Sorgeloos and Trotman (1991) provide a comprehensive review of many of its biological features. *Artemia* is now found worldwide because of introductions not only for purposes of local production for aquaculture but also because brine shrimp have been and are widely used by managers of solar salt fields as grazing organisms to control excess growths of phytoplankton. It appears that *Artemia* does not occur naturally in Australia, however. Other brine shrimp occur there, most in the endemic genus *Parartemia*, but in other genera as well in only moderately saline lakes. Like *Artemia*, *Parartemia* can tolerate salinities in excess of 300 ppt, but since it cannot develop haemoglobin it does not tolerate salinities quite as high as those tolerated by *Artemia* (which can develop haemoglobin).

Other crustaceans, though less well known than *Artemia*, may be equally important in some salt lakes. They include representatives of all the free-living copepod groups, cladocerans (Fig. 3.6), ostracods, and amphipods. Special note should be accorded the unique isopod of salt lakes, *Haloniscus searlei* (Fig. 3.7). This is derived from terrestrial ancestors and endemic to Australia.

Several groups of insects occur. *Ephydra*, the brine-fly (Fig. 3.8), is frequently present in certain regions, but other dipterans (e.g. species of *Tanytarsus* [chironomid], *Culicoides* [ceratopogonid], and *Aedes* [culicid]) may be common in particular lakes. Non-dipteran insect groups are well represented in lakes of moderate salinity by species of corixids (Hemiptera), dragon- and damsel-flies (Odonata) and beetles (Coleoptera). Other insect groups are less well represented if at all, especially the mayflies and stoneflies, but many insect groups have at least some species found in moderately saline if not highly saline lakes (but even these may have one or more species found in highly saline lakes, e.g. larvae of the trichopteran *Symphitoneuria wheeleri* can tolerate up to 175 ppt in some Australian coastal salt lakes although the order otherwise is not one characteristic of salt lakes).

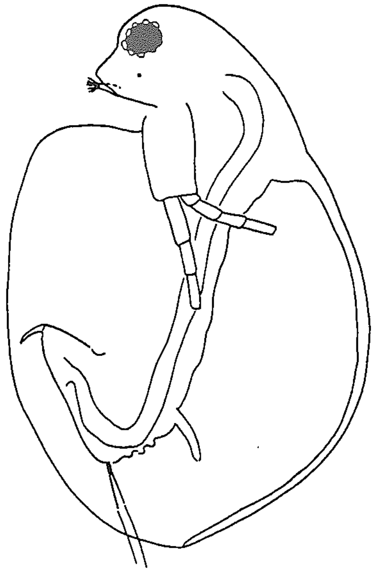

Fig. 3.6 *Daphniopsis*, a cladoceran of moderately saline lakes in Australia, South America, Tibet, and some Antarctic islands. After Smirnov and Timms (1983).

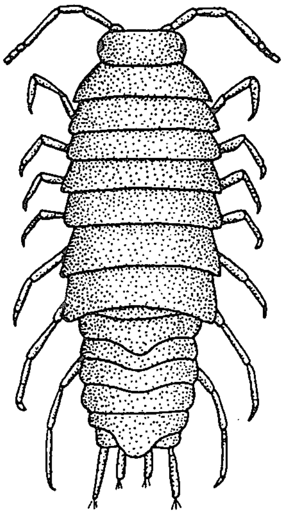

Fig. 3.7 *Haloniscus searlei*, an oniscoid isopod endemic in Australian salt lakes.

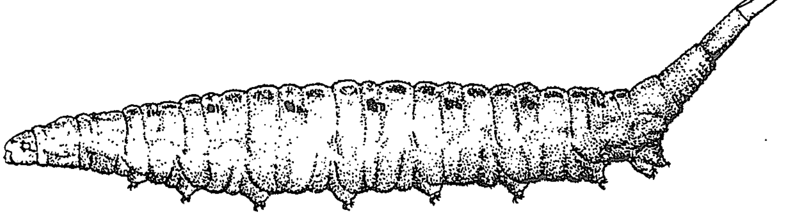

Fig. 3.8 *Ephydra* larva. A dipteran frequently found in salt lakes.

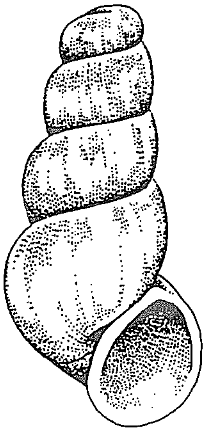

Fig. 3.9 *Coxiella*, a gastropod endemic to Australian salt lakes.

Non-arthropod invertebrate groups not already discussed and sometimes to be found in saline lakes include *inter alia* cnidarians, nematodes, turbellarians and gastropod molluscs. The occurrence is patchy, however. The only snail recorded from a highly saline lake is *Coxiella* (Fig. 3.9), a genus confined to Australia, though with some related forms in southern Africa. Nematodes and turbellarians are more widespread, but again records are patchy. Uncommon, rare or invertebrates never encountered in salt lakes but often common in freshwater lakes conspicuously include notostracans, conchostracans, sponges, bryozoans, nemerteans, leeches, hydracarines and bivalve molluscs.

The vertebrates of saline lakes are mainly fish and birds. Amphibians, reptiles and mammals do not occur apart from the odd representative in lakes of moderate salinity. The Caspian seal is a notable member of this group (see section 6.2).

A large number of species of fish has been recorded from permanent salt lakes (and from temporary ones too), but for the most part these records involve lakes of salinity less than 50 ppt and the fish recorded also occur in fresh waters. Most fish found in salt lakes, therefore, are essentially halotolerant freshwater forms. A few of these fish can tolerate salinities as high as 100+ ppt, but the number of species actually confined to inland salt waters seems to be very limited. *Oreochromis alcalicus grahami* (formerly known as *Tilapia grahami*), the soda lake fish of East Africa, is one. It was first described from hot alkaline streams bordering Lake Magadi but it has now been introduced to Lake Nakuru. Species of *Cyprinodon* may provide other examples.

None of the fish found in saline lakes has any method of withstanding desiccation when the lakes dry and so are usually absent from temporary saline lakes. Where they do occur in these, they originate from streams and rivers which have filled the lake. Fish found in solar salt ponds represent an attenuated selection of marine species. Some of these, it may be noted, are remarkably tolerant; *Atherinosoma microstomum*, a fish found in Australian salt ponds, can tolerate salinities up to 100 ppt.

The best known birds associated with, and indeed confined to, salt lakes are flamingos (Fig. 3.10; Ogilvie and Ogilvie, 1986). There are five species found in central and South America, Asia, Africa and southern Europe (Table 3.1). Fossil species are known from North America, Australia and other parts of Europe. According to species, flamingos are herbivorous filter-feeders on blue-green algae (e.g. *Spirulina*) and other phytoplankton or feed on small invertebrates.

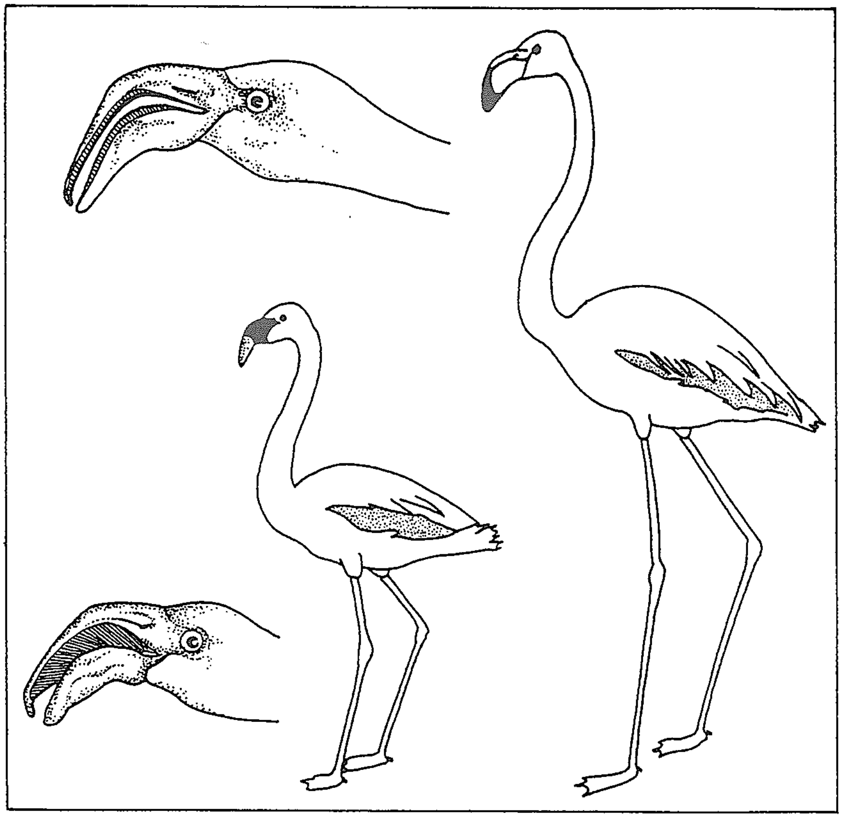

Fig. 3.10 Drawings of the general appearance and beak structure of the two commonest flamingos, the Lesser and Greater flamingo. Note: the Lesser flamingo is smaller, has a dark red bill with a black tip, and its legs are bright red. The Greater flamingo is larger, has a pale pink bill of which the outer half is black, and its legs are bright pink. After P. Scott and G. Troughton.

Table 3.1 Species of flamingo and their distribution.

Species	Common name	Distribution
Phoenocopterus ruber ruber	Caribbean flamingo	Caribbean Galapagos Is.
P. ruber roseus	Greater flamingo	S. Europe, Africa, Middle East, Central and SW Asia
P. chilensis	Chilean flamingo	S. America
Phoeniconaias minor	Lesser flamingo	Africa, NW India
Phoenicoparrus andinus	Andean flamingo	S. American Altiplano
P. jamesi	James' flamingo	S. American Altiplano

The association of flamingos with salt lakes has somewhat obscured the fact that a number of other birds is closely associated with salt lakes. A few of these, like the flamingos, are only rarely found elsewhere (e.g. the banded stilt, *Cladorhynchus leucocephalus*), but most are also to be found at freshwater localities and use salt lakes in a facultative way for feeding, nesting and for refuge. Nevertheless, salt lakes may be very important in the maintenance of viable populations of these species. Mono Lake in California, for example, plays a critical role in the survival of several bird species. Of these, eared grebes (*Podiceps nigrocollis*), Wilson's phalarope (*Phalaropus tricolor*) and California gulls (*Larus californicus*) seem to be more or less dependent on seasonally abundant invertebrates in this lake. Many other species feed, nest or find refuge at Mono Lake (see section 6.6). Mar Chiquita (section 6.7) hosts over 500,000 birds annually and is on the major migratory route of many shorebirds.

The above discussion is only concerned with the biota of salt lakes when these contain water. A much less diverse, but nevertheless distinctive biota is also associated with many dry salt lakes.

3.3 THE EXTENT OF DIVERSITY

It will be clear from the above discussions that fewer species are found in salt lakes with high salinities than in lakes with low salinities. Overall, in other words, salinity and diversity are inversely related. As a general rule of thumb, species richness (numbers) and diversity decrease sequentially from freshwater through hypo-, meso- and hypersaline lakes (Fig. 3.11). The biota in this sequence has frequently been categorized into (1) halotolerant freshwater forms (the shorter description, haloxenes, is rarely used), (2) halophilic forms or halophiles (forms typically found in lakes of moderate salinity but extending sometimes into waters of low salinity or even into fresh waters), and (3) halobiontic forms or halobionts (forms typically found in highly saline lakes). For several reasons, but especially to avoid confusion with regard to the term halophilic, now frequently applied to the biota of all salt lakes on a comprehensive basis irrespective of salinity, it is probably best to abandon the use of these categories. The relationship between salinity and biodiversity, it is important to add, is not at all close within individual lakes or for particular series of lakes. In these, there may be no significant relationship between salinity and diversity over wide ranges of salinity.

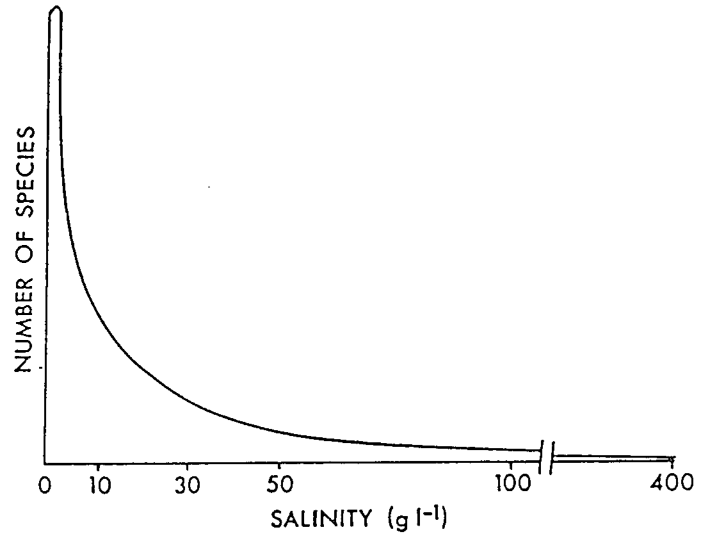

Fig. 3.11 Relationship between species richness and salinity. After Hammer (1986).

The explanation for the overall correlation between salinity and species richness and diversity is that elevated salinities provide a physiological stress for aquatic organisms and as this stress increases fewer and fewer of them evolved appropriate mechanisms to deal with it. As for the lack of correlation within wide ranges of salinity, one explanation is that the physiological resolution of how to cope with a particular level of salinity enables the species in question to tolerate a general range of salinity: in other words, once an organism has evolved mechanisms to cope with, for example, a salinity of 200 ppt, this mechanism enables it to cope with salinities between 200 and 300 ppt, and, to provide an example at the other end of the salinity scale, once a freshwater organism has developed some degree of tolerance to salinities >3 ppt, this tolerance enables it to inhabit salinities between 3 and 20 ppt. A corollary to this explanation is that, within the ranges of salinity tolerated, factors other than salinity (especially biological ones such as predation, competition, parasitism) may then be more important as determinants of species presence/absence and abundance (Williams, in press).

We are a long way yet from knowing what determines the distribution and abundance of species within salt lakes. It seems, however, that salinity is not the only determinant and may be much less important than was previously thought. It is perhaps most important at the lower end of the salinity spectrum, that is, in hyposaline waters. In this context, the decreased solubility of oxygen in waters of increasing salinity should be recalled. The decreased availability of oxygen in saline lakes (see section 2.4 and Table 2.3) may be at least as important a physico-chemical constraint as elevated concentrations of salt are.

Another element determining salt lake biodiversity is geographical location, both at a continental and regional scale. Considerable differences occur in the extent of diversity between and within continents. On a continental basis, the greatest diversity of salt lake organisms appears to occur in Australia. In that continent, for example, several crustacean groups (anostracans, copepods, ostracods, cladocerans) have speciated in salt lakes on a scale not evident in salt lakes on other continents (De Deckker, 1981, 1983). But, even so, the biota of salt lakes on all continents shows considerable degrees of diversity and endemism so that it is no longer valid to claim, as once it was, that the over-riding biological feature of salt lakes worldwide is their cosmopolitanism. Differences between continents need no explanation in a book of this sort. Note only that historical events, geographical isolation, and climatic change are the most likely factors involved.

Within continents, the extent of diversity and the sorts of biota present are also determined by geographical location in that this relates in particular to present and past climates. For example, the biota of rarely-filled episodic salt lakes in arid regions of Australia is different from that in salt lakes in less arid regions where water may be present all the time or present in a predictably seasonal way. An explanation that has been offered for this is that episodic lakes provide poor sites for evolution: their biota largely consists of species with good dispersal mechanisms (Williams and Kokkinn, 1988).

Regional differences may also occur between similar lakes in similar climatic regions. Those factors which explain continental differences are again probably important. Finally, it may be noted that substantial differences between lakes may occur even at the local level (e.g Timms, 1993, in press). These differences probably result from chance and local hydrological differences which determine the periodicity and duration of water in lake basins.

Human interference has somewhat complicated natural patterns of diversity. *Artemia*, for example, has been widely dispersed by managers of solar salt ponds, aquaculturalists and others. This dispersal has paid scant regard to origins or possible biological impacts. Fish have been introduced into some lakes for angling or other purposes (the introduction of the East African soda lake fish into Lake Nakuru has already been mentioned). And in a few cases, wholesale introductions have been made in attempts to improve lake productivity or usefulness. The Aral Sea provides a case in point. The biota of this lake was progressively 'supplemented' with fish and invertebrates from 1927 onwards. The Salton Sea, an artificially (and accidentally) created salt lake in California, has a dense population of barnacles introduced from the marine environment!

3.4 ADAPTATIONS

A number of physico-chemical environmental conditions distinguishes salt lakes apart from the fact that they have salinities >3 ppt. For organisms to survive in salt lakes, none of these conditions must exceed the tolerable limits of the organism in question at any time in its life-cycle. Of conditions seen as distinctive (either singly or in combination, uniquely or generally, or permanently or intermittently), the following are generally perceived as the most important of those which are biologically restrictive and to which the biota must adapt if it is to live in salt lakes: high salinity, high temperatures, high light intensities, low oxygen concentrations, environmental variability (including especially variability in the amount of water present and water-levels), and habitat isolation. Adaptations to these conditions have often taken different paths in different taxonomic groups.

Adaptations to high salinity are of various sorts. The simplest merely involves the development of an increased cellular tolerance to elevated external salinities. Others fall roughly into two types: those involving osmoconformity and those involving osmoregulation. Osmoconformers have adapted by increasing the concentration of their internal medium to an osmotic value near that of the external medium. Various compounds (osmolytes) have been used to achieve this balance. The halobacteria maintain high internal pressures by accumulating large concentrations of inorganic ions, especially potassium. Cytoplasmic proteins have undergone wide amino acid substitution to enable them to work in the presence of high concentrations of inorganic solutes. In the Cyanobacteria, both inorganic and organic osmolytes are involved. *Dunaliella* uses glycerol as its osmolyte. *Lamprothamnion papulosum* (a charophyte) uses potassium, chloride and organic solutes. *Ruppia*, the most salt tolerant of higher plants in salt lakes, uses amino acids as osmolytes (proline), as apparently do many of the salt tolerant plants found growing around the margins of salt lakes (e.g. *Sueda, Salicornia*).

Less is known about the methods used by animals to osmoconform. Note, however, that many animals which conform do so over only part of the salinity range within which they occur. Thus, the gastropod *Coxiella* weakly osmoregulates at low salinities and osmoconforms at higher salinities (at excessively high salinities it simply isolates itself from the external medium by tightly closing its operculum over its shell opening). Most invertebrates found in salt lakes appear to osmoregulate (Bayly, 1972). They have physiological mechanisms which can regulate the concentration of their body fluids to an osmotic pressure above or below that of the external medium. Fig. 3.12 illustrates this for *Artemia* and *Haloniscus searlei*. A degree of body impermeability is of some value in this matter. The basic mechanism in general is either to excrete a dilute urine and retain salts or imbibe the external medium and excrete unwanted salts. Many birds associated with salt lakes have special salt-excreting glands. However, to survive many must also have access to fresh water.

Adaptations to high temperatures have not been well studied. It seems, however, that the osmolytes used by *Dunaliella*, halobacteria and Cyanobacteria also serve to reduce the effect of high temperatures on enzyme systems in these organisms. Many organisms of salt lakes escape intolerably high temperatures simply by moving to cooler, sheltered areas such as beneath vegetation and into the uppermost layers of bottom sediments. Adaptations to high light intensity may also involve behavioural adaptations of this sort, but additionally many organisms possess carotenoid pigments which act as light quenchers. Such pigments are possessed by a diverse range of organisms living in salt lakes including *Dunaliella*, halobacteria and copepods.

Of adaptations to low concentrations of oxygen (hypoxia), the following seem to be the most important: behavioural responses, the development of respiratory pigments, respiratory regulation and a tolerance to the products of anaerobic respiration. The development of various forms of haemoglobin by *Artemia* at low concentrations of oxygen merits particular note.

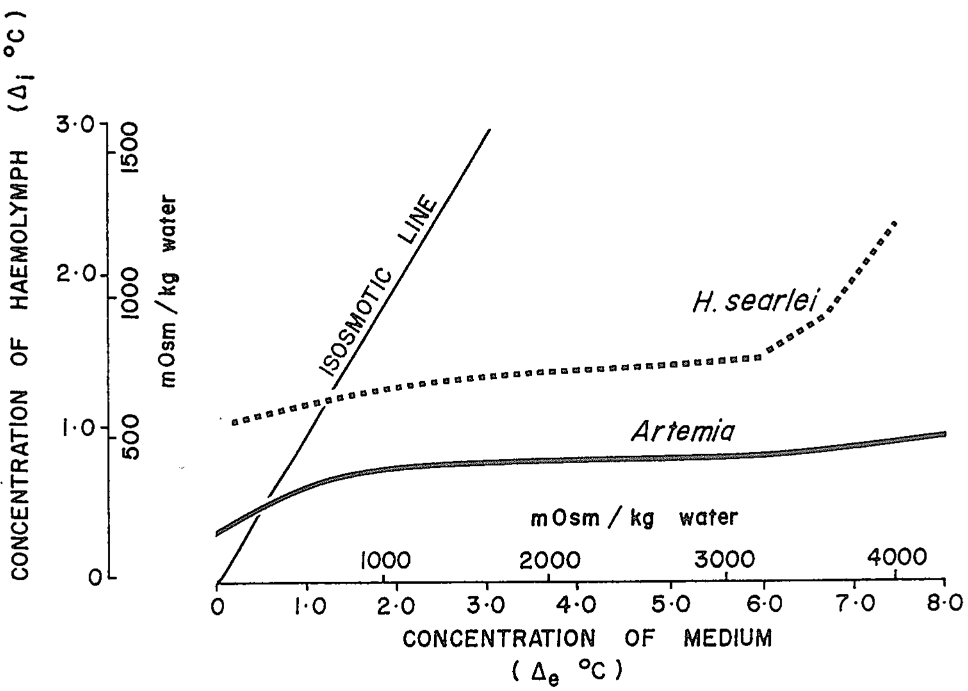

Fig. 3.12 Osmoregulation in *Haloniscus* and *Artemia*. The graph compares the relationship between the concentration of the haemolymph and the external medium. Where the lines fall below the isosmotic line, active osmoregulation is occurring. After Bayly and Ellis (1969).

For organisms in temporary salt lakes, an essential prerequisite for survival is the possession of adaptations to overcome the dry season, i.e. adaptations to survive desiccation. According to species, all stages of the life-cycle may serve as the resistant body; animals may resist desiccation in the egg phase, or as cysts, juveniles, larvae or adults; plants may have resistant cysts, spores, seeds or vegetative parts.

For adult animals, one method to avoid drying is simply to move to another, more congenial locality. This method is restricted to birds and certain insects. Thus, when their habitats dry up, flamingos and banded stilts at temporary salt lakes survive by flying to other water-bodies. Survival as adults in species unable to leave a dried lake usually involves burrowing into sediments or finding shelter in damp situations elsewhere (e.g. *Haloniscus*). *Coxiella* responds in the same way that it does to extreme salinities and survives within its tightly closed and more or less impermeable shell. Within their protective shells, adults can withstand low concentrations of oxygen, high temperatures and desiccation, as well as extremes of salinity, for many months.

A few animals survive dry phases as encysted embryos. The best-known of these is *Artemia*; it survives in cysts containing dormant embryos which in their dehydrated state can withstand almost complete desiccation, very high and low temperatures, and salinity extremes. Most animals of salt lakes, however, survive desiccation as resistant, dehydrated eggs. Frequently, resistant eggs alternate with non-resistant eggs within a life-cycle. In *Daphniopsis* (Fig. 3.6), for example, non-resistant eggs are produced asexually during the first part of the time when lakes contain water, and resistant eggs are produced sexually in special epphippia or sacs towards the end of the aquatic phase of the lake. In this sort of life-cycle, we see yet another adaptation possessed by animals of salt lakes: modifications of the life-cycle which take into account the instability and fluctuations of the environment. Of particular adaptive value here is the possession of the ability to detect environmental change, that is, the ability to react to environmental 'cues'.

Plants show similar adaptations in life-cycles. In this regard, it should be remembered that for all organisms life-cycle adaptations essentially involve the differential allocation of resources between survival, growth and reproduction. Species in temporary salt lakes must allocate more resources to survival and reproduction and less to growth than species of permanent salt lakes. A study of species of *Ruppia* in temporary and permanent salt lakes in South Australia illustrated this point well (Brock, 1981). The species of temporary lakes (the annuals, *Ruppia polycarpa* and *R. tuberosa*) allocated more resources to reproduction and survival in the form of seeds, turions (asexual perennating structures) and rhizomes than did the perennial species (*R. megacarpa*) found in permanent lakes.

Finally amongst important adaptations to life in salt lakes are those which have arisen in response to the relative isolation of the lakes, i.e. effective dispersal mechanisms. However, perhaps more importance has been attributed to these adaptations than is justified: whilst good dispersal mechanisms are likely to be important for organisms of episodic salt lakes, they are perhaps less important for those living in permanent or intermittent salt lakes. Of interest in this context is the recent observation that the fauna of a series of more or less temporary salt lakes in a semi-arid part of Australia includes many regionally restricted species (Timms, 1993). This suggests that effective dispersal from a dried lake is not a significant part of the life-cycle for at least some of the species present - for these species, the best strategy for survival is to remain in the same locality where reproduction was successful in the previous generation.

3.5 SALT LAKES AS ECOSYSTEMS

Given the view sometimes espoused that salt lakes as ecosystems are quite different from other sorts of aquatic ecosystem (e.g. Vareschi, 1987), it is appropriate to conclude this chapter with a brief comment on the integrity of salt lakes as ecosystems.

Ecosystems can be defined as relatively discrete areas of the natural world where causal, interdependent relationships operate between living and non-living components, where energy flows along defined pathways, and where essential elements are part of biogeochemical cycles. All of these phenomena characterise salt lakes. It is true that salt lakes are different in certain respects from some other aquatic ecosystems, especially perhaps in having less trophic (and taxonomic) complexity and different levels of persistence and stability. However, these features scarcely alter the fundamental integrity of salt lakes as ecosystems. All ecosystems are different; in salt lakes, differences are of degree only.

CHAPTER 4

VALUES

4.1 INTRODUCTION

In so far as the effective management of any natural resource should be concerned to maximize on a sustainable basis the values of the resource in question, it is important to recognize what these values are. This chapter outlines these values for inland saline waters.

Two broad categories of value can be distinguished for salt lakes: economic and non-economic. It is possible to place monetary estimates on the former with relative ease, but non-economic values cannot (or cannot easily) be estimated in this way. As a result, non-economic values of salt lakes are underestimated, and it is only when they have been degraded following mismanagement that true estimates of their value become apparent. A clear example is provided by the mismanagement of the Aral Sea (see section 6.2). It was only when this lake had been severely degraded by the diversion of inflow waters for purposes of irrigation (on which monetary estimates could be placed without difficulty) that its many non-economic values became evident (including its values as a moderator of the local continental climate, as a focus of local cultural interest, and as an aquatic ecosystem with many conservation values). In the long-term, non-economic values, both in the Aral Sea and other salt lakes, may prove to be more important than short-term economic gains causing salt lake degradation and environmental abuse.

These comments do not imply, of course, that all activities involving the economic use of salt lakes lead to degradation and environmental abuse. That is far from the case. What is implied is the importance of recognizing that the economic use of salt lakes must involve management which takes account of non-economic values. The effective management of salt lakes should embody the 'wise use' principles of Ramsar (an international, intergovernmental convention concerned to conserve wetlands) and the knowledge that salt lakes have many unique features which distinguish them from freshwater lakes, as indicated in chapters 2 and 3.

4.2 ECONOMIC VALUES

Salt lakes as sources of minerals and other useful products

Salt lakes have long been recognised as sources of useful minerals. This is especially true with regard to salt (sodium chloride), for which humans have apparently always had both need and craving. In historical times, salt came from three principal sources: from sea-water by evaporation, from salt lake brines or sediments, or from rock salt. In addition to use as a food additive and preservative, it was used as a currency, as a taxable item, and for barter. Salt is important now mainly because it is a basic industrial resource. Immense amounts are needed (~ 200 million tonnes each year). Whilst much of it comes from rock salt, vast quantities also come from solar evaporation of sea-water in shallow coastal ponds (generally referred to as solar salt fields, from salt harvesting at inland lakes, and, in some areas, from solar evaporation of saline ground waters pumped to the surface (see section 5.3). The production of salt at coastal solar salt fields occurs throughout the warmer latitudes, and often where it is far too arid for natural salt lakes to develop.

Salt (sodium chloride) is only one of many useful inorganic products recoverable from salt lake brines or sediments (Reeves, 1978). Other products are of three sorts: *evaporites* (Warren, 1989), *clastics* (derived materials), and *authigenics* (pore sediment precipitates).

The major evaporite minerals of economic significance, and a brief indication of uses, are listed in Table 4.1. The composition of various evaporites is listed in Table 4.2. Not listed are various commercially useful evaporites of generally only local occurrence, or evaporites which rarely develop local concentrations but which have recently become of increased interest, e.g. lithium. Uranium salts are also of increased economic importance and not listed in Table 4.1. Unlike lithium salts, however, high local concentrations may develop. Uranium salt deposition illustrates well the spatial sorting of evaporites frequently displayed in salt lake sediments and of interest to miners.

Table 4.1 Major evaporite minerals and their uses.

Salts	Minerals	Uses (including manufacture)
Calcium, magnesium carbonates	Aragonite, dolomite, calcite	Cement, fluxes, chemicals, building materials
Sodium carbonate	Natron, trona	Washing soda, baking soda
Calcium sulphate	Gypsum, anhydrite	Tiles, plaster, fillers, fertilizers, paints, insecticides
Potassium, magnesium, sodium sulphates	Mirabilite, polyhalite, thenardite, glauberite, langbeinite, epsomite, kainite	Fertilizers, glass, soap, matches, explosives, dyes, tanning agents, paper and cardboard, textiles, heavy chemicals, medicines, paints
Sodium, potassium chlorides	Halite, sylvite	Condiments, soap, dyes, glazes, cement, preservatives, insecticides, drugs, chemicals, fertilizers
Borates	Colemanite, ulexite	Porcelain, glass, enamels
Nitrates	Nitre, soda nitre	Fertilizers, explosives, chemicals

Table 4.2 Chemical composition of some common evaporite minerals.

Mineral		Composition
Carbonate		
	Aragonite	$CaCO_3$
	Calcite	$CaCO_3$
	Dolomite	$CaCO_3.MgCO_3$
	Gaylussite	$Na_2CO_3.CaCO_3.5H_2O$
	Nahcolite	$NaHCO_3$
	Natron	$Na_2CO_3.10H_2O$
	Trona	$Na_2CO_3.NaHCO_3.2H_2O$
Sulphates		
	Anhydrite	$CaSO_4$
	Epsomite	$MgSO_4.7H_2O$
	Glauberite	$CaSO_4.Na_2SO_4$
	Gypsum	$CaSO_4.2H_2O$
	Langbeinite	$K_2SO_4.2MgSO_4$
	Mirabilite	$Na_2SO_4.10H_2O$
	Polyhalite	$K_2SO_4.MgSO_4.2CaSO_4.2H_2O$
	Thenardite	Na_2SO_4
Chlorides		
	Bischofite	$MgCl_2.6H_2O$
	Carnallite	$KCl.MgCl_2.6H_2O$
	Halite	$NaCl$
	Kainite	$4KCl.4MgSO_4.11H_2O$
	Sylvite	KCl
Borates		
	Borax	$Na_2B_4O_7.10H_2O$
	Colemanite	$Ca_2B_6O_{11}.5H_2O$
	Ulexite	$NaCaB_5O_9.8H_2O$
Nitrates		
	Nitre	KNO_3
	Soda nitre	$NaNO_3$

Of clastics, sands, gravels, silts and clays are the most important. The commonest significant authigenics include pyrite (FeS_2), marcasite (FeS_2), sulphur, gypsum, and various silicates. Zeolites (hydrated alumino-silicates) have attracted much attention because of their unique hydrating, catalytic, ion exchange and other chemical properties.

Finally, mention is made of various hydrocarbons in salt lakes. Asphalt (more directly, asphaltites) has been recorded from the Dead Sea from the earliest times, and until the nineteenth century it was a local fuel (Nissenbaum, 1993). Its most dramatic occurrence is as large floating blocks, some many tonnes. Asphaltites and other hydrocarbons in salt lakes evoked much interest in the early twentieth century because it was hoped that they indicated that oil deposits were located nearby. These hopes were unfulfilled, but there has been renewed interest in the role that salt lakes have played in shale genesis. The interest has been stimulated by the recognition that marine evaporites overlie carbonates containing an estimated 50% of world oil supplies (Kirkland and Evans, 1981). There is considerable speculation that under certain past conditions some shallow saline lakes could have given rise to oil-bearing deposits. There is no doubt, in any case, that evaporite deposition, the carbon cycle, and the formation of fossil oil are closely linked. Recent opinion is that localities where carbonates deposited and salinities fluctuated between ~40 and 120 ppt are the source of most global oil reserves (Javor, 1989).

Salt lakes as a source of water

The water which flows into salt lakes is another mineral of value. It is most valuable whilst fresh and before entry to the lake. There are several projects involving diversion of freshwater inflows from salt lakes; all, predictably, have significant impact upon the lake concerned. Several examples are discussed in chapter 6 and section 5.2 provides a general discussion of this matter.

Water from saline lakes is also directly exploitable. Much research on this is in progress. Mostly it involves research on (1) agricultural problems relating to secondary salinisation (particularly concerning halotolerance of food crops), (2), explorations of the agricultural use of sea-water, or (3), the carefully managed use of slightly saline and sometimes ephemeral water to complement fresh waters. Despite some problems, there is optimism about this use of saline water. Given the exploitative urge and the need of modern society, there is little doubt that water from inland saline lakes will be subject to ever-increasing use of this sort, particularly water from lakes of only moderate salinity and relatively constant level.

Salt lakes as a source of energy

As discussed earlier (chapter 2), meromictic salt lakes sometimes have monimolimnia with persistently higher temperatures than occur in surface layers. Temperatures may even reach 70 °C. The high temperatures result from the retention of solar energy. Such lakes are known as 'heliothermal' lakes. The fact that heat stored in 'heliothermal' lakes could provide energy for man's use has long been recognised, but it was not until relatively recently that the idea of using it was seriously considered, and the technology of artificial heliothermal lakes, so-called solar ponds, investigated.

Various sorts of solar ponds have been investigated, from those characterised by a gradient toward the pond bottom (salt gradient solar ponds), to those where a polymer gel replaces the mixolimnion. Salt gradient solar ponds appear the most promising in practical terms; their structure and operation are, in principle at least, simple. Structurally, they simulate natural heliothermal localities, but maximise those features enhancing energy retention and minimise those causing energy loss. Usually just a few metres deep, they contain strong salt solutions, mostly sodium chloride, with concentrations which increase downwards (Fig. 4.1). There are three layers: a bottom convecting layer (monimolimnion) with a salt concentration of ~ 150-

250 ppt; a middle non-convecting or gradient zone (chemocline), where salinity decreases upwards; and an upper, relatively thin convecting layer (mixolimnion) with a salinity of ~ 20 ppt. The two upper layers allow significant amounts of solar energy to pass through. On reaching the pond bottom, most of the solar energy is absorbed and heats the bottom layer. Heat is trapped by the middle non-convecting gradient zone which acts as an insulator. Relatively fresh water needs constantly to be added as a surface flush to compensate for evaporative loss and to remove salt that has diffused upwards (this salt is usually recovered from the overflow in nearby evaporating ponds). Whilst surface temperatures reflect ambient values, bottom temperatures begin to rise some weeks after pond construction and may exceed 100 °C in certain experimental situations. Generally, temperatures are kept between 50 and 90 °C by removal of hot brine. To obtain the energy in useful form, the hot brine may be passed through a heat exchanger where under pressure it vapourises a liquid of low boiling point (e.g. freon). The vapourised liquid drives an electric generator. Cooled brine is returned to the pond.

Solar ponds have been constructed in several countries, including the US, Israel, and Australia. However, a number of problems has arisen so that interest in them as alternative sources of power has waned. Some major problems include salt availability, diffusion, meteorologically induced instability of the upper layer, and evaporation.

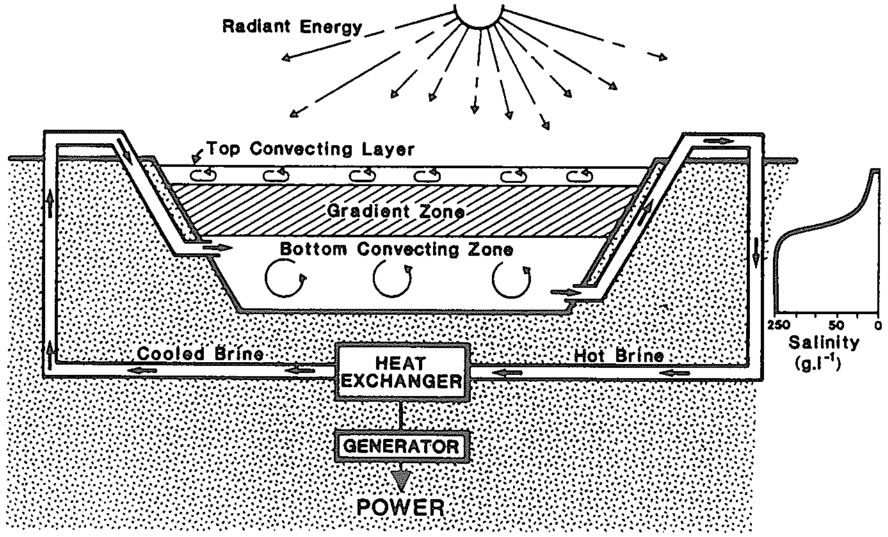

Fig. 4.1 Schematic layout of a salt gradient solar pond. The salinity gradient is indicated at far right.

Algal production and products

Several blue-green (cyanobacterial) and true algae found in salt lakes have proved to be of commercial interest. Thus, both *Spirulina platensis* (Fig. 3.2a) and *S. maxima* (blue-green algae) have particularly high concentrations of protein (up to 70%) and compare favourably with soya in this respect. Additionally, *Spirulina* has a diverse range of amino acids as well as vitamins and growth factors (especially Y-linolenic acid and its nucleic acid and cholesterol contents are beneficially low (<5% dry weight). *Spirulina* has attracted considerable international attention as a food. There is also considerable interest in it as biomass for the extraction of natural products and biochemicals, and for the biological production of hydrogen.

Several features of *Spirulina* are propitious for commercial production. First, high densities can be easily maintained in unispecific culture. Second, *Spirulina* is relatively easily harvested compared with algae or single-celled microorganisms. And third, its growth requirements apart from water appear minimal, and its tolerance to various environmental factors is extremely wide. Another species of obligate halophilic cyanophyte has also been shown to be rich in protein (up to 76% of dry weight) and amino acids: *Aphanothece halophytica*. It has been suggested that this species too could become a valuable food organism.

The green alga *Dunaliella* (Fig. 3.2b), even more common in saline lakes because of its preference for chloride not carbonate environments, has also attracted considerable commercial attention. This is because (1), it accumulates large amounts of glycerol as an osmolyte, (2), certain species develop large quantities of β-carotene under particular conditions, and (3), it is rich in proteins. All of these products are most useful. Glycerol is an important organic compound currently manufactured for the most part from petrochemicals and as a by-product of soap and fat manufacture. It has many uses, and is an ingredient of paints, resins, toothpastes, cosmetics, drugs, food and explosives. β-carotene is of commercial use as both provitamin A and as a natural colouring agent. Additional metabolites of *Dunaliella* of potential commercial interest include lipids, sterols (especially ergosterol), enzymes and other vitamins (e.g. tocopherols). The advantages of commercial production of *Dunaliella* have been summarised as follows: it gives three immediately useful products, viz. glycerol, β-carotene and protein; the best conditions for production are in semi-arid areas where the most abundant water available is often saline; it results in a more digestible product than does most algal production; and the conditions of production are such as generally to exclude unwanted contaminants.

Bacterial products

Little commercial exploitation of products from the microbial life of saline lakes has taken place so far. However, such exploitation will almost certainly develop because of the increased industrial need for organic catalysts (enzymes), the only practical source of which are living organisms, mostly microbial.

Modern technology utilizes enzymes in many industrial conversion processes (usually via fermentation) to produce such materials as antibiotics, drugs, organic acids and vitamins. Important disadvantages in their use is the usual need for high standards of sterility, and carefully controlled storage and operative conditions. Homologous enzymes from halophilic bacteria may circumvent disadvantages of this sort. Additionally, some enzymes from halophilic bacteria will probably possess unique characters of their own, and give rise to entirely new fermentation processes. Techniques of genetic engineering may prove to be of considerable utility here.

Halophyte production

There are few truly aquatic macrophytes of highly saline inland waters (chapter 3), and none seems of any significant direct economic value. Some direct use has been made of macrophytes in moderately saline waters, and species of *Juncus* in Egyptian saline basins have long been used in making mats, ropes, baskets and various medicines. A different picture emerges when the much greater diversity of macrophytes characteristically associated with marginal and only rarely inundated areas of saline ground around salt lakes is considered. In many parts of the world, this vegetation, especially the chenopods, has been important as a forage crop. In certain regions it has also provided local sources of medicines and ornamental and food plants.

With the expansion of secondarily salinised land in irrigated areas (and elsewhere) in semi-arid regions, and the increasing need to bring marginal agricultural land into useful production, halophytes growing around salt lakes are of increasing interest; there is now clear recognition of their considerable economic potential in a number of ways. Not the least potential value is their halotolerance. Indeed, the availability of genetic engineering, whereby halotolerance can be transferred between species, may mean that this value is by far the most significant. In short, halophytes have immense potential as genetic banks of halotolerance.

Animal products

A variety of animals found in salt lakes may serve as food for humans or other animals. It includes invertebrates and vertebrates, and natural and introduced species.

The most important invertebrate is undoubtedly *Artemia* (Fig. 3.5). Dried, it provided food for certain people living near salt lakes, but a much more important and recent use of *Artemia* is in the aquaculture industry. In 1933, it was found that newly-hatched *Artemia* larvae were an attractive and nutritious food for fish fry. From then on, the use of *Artemia* larvae has greatly expanded as a significant food base in the culture of many species of fish, crustaceans and molluscs. For the most part, the market need is satisfied by the provision of dried cysts from which live larvae are hatched as required. These cysts are supplied from a variety of sources, including in particular coastal solar salt field pans, coastal pans designed for *Artemia* culture (as in various parts of Asia), and natural lakes. The highly saline effluent ponds of certain industrial treatment plants may be another type of exploitable locality. Whilst cysts have been the focus of attention, interest is increasingly turning to the potential of adult *Artemia*. The main use of live and frozen adults is as pet food.

During the past few decades, culturing techniques, feeding requirements, nutritional value, hatching problems, strain variability, and many other matters associated with aquacultural use of *Artemia* have been the subject of numerous investigations. Many results have been summarised in a comprehensive series of texts which report the proceedings of international symposia on *Artemia* (Persoone et al., 1980; Sorgeloos et al., 1987; see also Browne et al., 1991). Compared with the value of *Artemia*, other salt lake invertebrates are of little importance. Ephydrid fly larvae (Fig. 3.8) of Mono Lake, California, used to be harvested for food by local Indians. *Brachionus plicatilis* (Fig. 3.4), a rotifer common to salt lakes more or less worldwide, plays a role similar to but not as important as *Artemia* as a food for fish fry; usually, however, supplies are obtained from mass culture. And *Diaptomus connexus*, a copepod of North America, has been collected from certain Saskatchewan salt lakes as a food for tropical fish. In Asia, many species of marine shrimps and prawns (e.g. *Penaeus* spp.), as well as oysters, are cultivated in coastal saline ponds which are not part of solar salt fields.

Certain other marine invertebrates have been successfully introduced into true salt lakes. Although not of direct use, they may become important food-chain items supporting fisheries. Thus, almost all invertebrates of the Salton Sea, an artificial salt lake of southern California, have been introduced. They support an important recreational fishery.

Fish, birds, and, in one special case, a mammal, represent salt lake vertebrates of economic interest. Several permanent saline lakes with salinities below 20 ppt support fish populations of commercial or recreational significance. Of natural populations of interest, those in the Caspian Sea, Issyuk-Kul and Qinghai are important Asian examples. Important North American examples are provided by populations in Pyramid and Walker Lakes, Nevada.

In addition to the natural occurrence of fish in saline lakes, many moderately saline lakes now support introduced populations, either perennially or intermittently. Whitefish (*Coregonus clupeaformis*) and pike-perch (*Stizostedion vitreum*) have been introduced into several saline lakes in Saskatchewan. An Australian example is provided by Lake Bullen Merri, Victoria. This slightly saline lake (~8 ppt) supports an important recreational fishery based on chinook salmon (*Oncorhynchus tshawytscha*) whose populations are entirely maintained by stocking. A rather special example is provided by Lake Quarun, Egypt. This lake used to be fresh and had a freshwater fishery. Rising salinity levels caused the demise of the freshwater fishery and its replacement by one based on fish introduced from the Mediterranean.

The bird most commonly associated with saline lakes, the flamingo (Fig. 3.10), has had a long history of exploitation. Though now officially protected throughout most of their ranges, flamingo eggs and flesh are still exploited in many places. Whether any natural population of flamingo could be harvested on a sustainable basis is doubtful, but huge populations are certainly supported by some solar salt fields. Many species of waterfowl also make intermittent use of certain salt lakes, either as refuges or feeding grounds.

Finally, brief mention is made of the Caspian seal (*Phoca caspia*). This used to be hunted for fur and meat; hunting is now strictly controlled.

4.3 NON-ECONOMIC VALUES

Recreational aesthetic and cultural values

Aquatic recreation has greatly expanded in many parts of the world during the past decades. Expansion has been accompanied by growth of various industries (boat-building, manufacture of fishing tackle, hotels, etc.). Most water-based recreation involves the sea or freshwater lakes, reservoirs or running waters, but in areas remote from the sea, or where fresh waters are scant or absent, salt lakes may satisfy particular recreational needs. The most useful salt lakes in this respect are deep permanent ones which sustain a recreational fishery.

There are many examples of salt lakes which satisfy all three classes of recreational demand recognised by water managers, namely, primary contact (swimming, water-skiing), secondary contact (sailing, fishing, etc.), and passive recreation (sight-seeing, bird-watching, etc.). Even more examples can be provided of lakes satisfying only one or two recreational demands.

A particularly important aspect of the recreational value of many salt lakes is their aesthetic value. This often makes them a significant tourist attraction within an area. Note that the tourist 'industry' is one of the fastest growing of all global economic activities at present, and in certain countries is the biggest employer of any commercial sector. The economic value of many African salt lakes is stressed in this respect. Lake Nakuru, Kenya, with its huge flamingo populations, and Etosha Pan, Namibia, with its abundant local wildlife, are outstanding examples. In Europe, the Seewinkel region of Austria and the Camargue of southern France, both of which include many salt lakes, annually attract thousands of bird-watchers and tourists. Mono Lake, California, does likewise in North America. Even Lake Eyre in central Australia, remote from any tourist facilities whatsoever and within the most arid of landscapes, is a short-lived recreational focus for hundreds of sightseers on the rare occasions it contains water. Attitudes to aesthetic values have been divided and have changed with time. Certainly, many early European explorers did not rate the aesthetic appeal of salt lakes highly when first sighted in remote areas.

Many large salt lakes have been of cultural significance during historical time and still are. Thus, the Aral and Caspian Seas figure prominently in the classical literature of central Asia, as does the Dead Sea in the history of the Middle East and eastern Europe (Nissenbaum, 1979). The Aral region is one of the ancient centres where civilization and agriculture arose, and primitive irrigation was practised in its basin as early as the sixth century B.C. No doubt many particular salt lakes of North and South America had special local cultural significance too. The cultural value of Mono Lake, California, to the indigenous Owens Valley Paiute Indians, for example, has been noted by Patten et al., (1987).

Finally, brief note may be made of the cultural significance of flamingos. Flamingo skins, flesh and eggs have long been trade items around the shores of the Mediterranean, and the ancient Phoenicians traded flamingo tongues which, according to the Roman Pliny, were a delicacy without which no Roman banquet was complete.

Therapeutic values

Salt lakes in many regions have long been thought to possess curative powers for a variety of human ailments. The medical basis for the claims remains indeterminate, but considerable credence was accorded the therapeutic values of of salt lakes in historical time, and some persists. Claims for the medicinal powers of the Dead Sea have long been held and it is possible to buy 'synthetic' Dead Sea salt which, it is alleged has abilities to relieve psoriasis and rheumatism. Bulgareanu (1993) alludes to the therapeutic properties of sediments in saline lakes in Romania. Some modern (as well as ancient) North Americans have faith in the medicinal powers of certain salt lakes. The Aztecs thought that Lake Texcoco had significant healing powers. Soap Lake (Washington) was (and is) visited by many seeking relief from various ailments. And Little Manitou Lake (Saskatchewan) was referred to as the "Lake of Healing Waters" by plains Indian tribes. Even now, a large indoor spa exists at the side of the lake, with associated clinics, medicinal bath-houses, and physiotherapy units.

Scientific and educational values

Salt lakes are of interest to the practitioners of several scientific disciplines: ecology, physiology, evolutionary biology, palaeolimnology, hydrology and geochemistry are among the more important. Much of this interest is relatively recent, and has followed an increased knowledge of the limnological features of salt lakes and their unique biota. Scientific interest will undoubtedly accelerate as this knowledge consolidates.

With regard to ecological interests, salt lakes have many unique features which make them important loci for studies. One is the greater ease with which whole ecosystem studies can be undertaken. Thus, many of the difficulties which beset ecosystem studies of freshwater and marine environments are minimized in salt lakes. Such difficulties include great species diversity, considerable habitat heterogeneity, lack of discreteness, and complex trophic relationships. These sorts of difficulty are minimized in salt lakes: in them, species diversity is relatively low, there is often considerable habitat homogeneity, they are discrete almost by definition, and the complexity of trophic-dynamic relationships or food-webs is reduced.

One important feature of the decreased biodiversity in highly saline lakes is the frequent absence of macrophytes and fish. These are important elements in many other sorts of aquatic ecosystem (and some saline ones too). The lack of macrophytes is especially important because it leads to a decrease in habitat diversity; allied with topographically flat lake basins, a frequent consequence is that, unlike most freshwater lakes, many shallow and highly saline salt lakes are quite uniform throughout their entire area in terms of water depth and the nature of their bottom sediments. Shallowness, moreover, generally leads to complete physico-chemical mixing throughout the water column.

Finally, whatever their depth or salinity, salt lakes are more discrete than almost all other ecosystems. Since they are the termini of closed drainage systems, influent material can leave only aerially or through the groundwater. Water does this by evaporation or by seepage, and there is some aerial loss of material by deflation and in the bodies of insects and birds. Nevertheless, compared with standing freshwater-bodies and running waters, salt lakes are significant 'sinks' or 'traps'. Their discreteness also lessens the conceptual difficulties determining ecosystem boundaries in ecosystem studies (cf. Walker, 1973) and enables a reasonable analogy to be drawn between isolated salt lakes and islands.

The relative ecological simplicity and discreteness of salt lakes are not the only reasons why salt lakes are interesting to ecologists. It is possible to regard salt lakes as a continuous series of ecosystems, from simple (the most saline) to complex (the least saline) for the study of *ecosystem attributes*. As well, salt lakes, particularly the most saline, are highly suitable as natural ecosystems on which to base 'microcosmic' studies. Here, microcosmic studies are taken to mean studies of laboratory microcosms or microecosystems involving just a few elements of the natural system. For microcosmic studies of fresh waters (complex ecosystems) a major difficulty has been the uncertainty about the extent to which results accurately predict natural events. Can results from *simple* microcosms based on *complex* ecosystems ever be extrapolated back? The relative simplicity of natural saline environments suggests that assumptions based on microcosmic studies of them will be nearer what happens in nature. Ecological studies of individual salt lake species, or more general ecological studies (e.g. Bayly and Williams, 1966), are also valuable in their own right: they make worthwhile descriptive contributions to our knowledge of how particular parts of the biosphere function, and how various species cope with the stresses of life in an environment which is a hostile for most life.

For physiologists, a key feature of interest is the nature of physiological adaptation to the stresses of life at high (and fluctuating) salinity, high light exposure, habitat ephemerality (in many if not all localities), and lowered oxygen tensions. The physiological resolution of these stresses has clearly been arrived at by a variety of organisms, from bacteria to vertebrates, thus providing a diversity of material for physiological research. In short, salt lake organisms offer examples of changes in molecular structure, metabolic pathways, and structure that can be related directly to easily identifiable external parameters.

With regard to the scientific interest of salt lakes to biologists other than ecologists or physiologists, special mention may be accorded the interest of evolutionary biologists. This has a two-fold origin. First, some salt lake or organisms (stromatolites and archaeobacteria) appear to be very ancient forms of life and thus may help shed light on how life on earth arose. Second, salt lakes themselves provide valuable loci for the investigation of evolutionary mechanisms.

The interest of palaeolimnologists in salt lakes stems from the sensitivity of these environments to climatic and tectonic change. Clearly, even the slightest change in, say, the ratio of precipitation to evaporation will profoundly affect a salt lake: it will become either more saline, more ephemeral, or dry on the one hand, or less saline and less ephemeral on the other. Most salt lake palaeolimnological studies until recently were more concerned with geological and physical analyses of sediments than with the analysis and interpretation of biological remains. The situation has changed. There is now a vastly increased perception that plant and animal remains preserved in salt lake sediments have a great deal to offer palaeolimnological analysis, and are as amenable to study and provide records as valuable as remains in freshwater sediments.

Finally, at least a brief note should be made of the large number of geological, geochemical and hydrological problems posed by the complexity of geological, hydrochemical and hydrological interactions in salt lakes (Eugster and Hardie, 1978). These attract large numbers of earth scientists. Many of these are aware that the study of contemporary saline lakes can provide clues to the nature of oceanic and continental evolution. Closely allied to many scientific values of salt lakes are educational values. At a time of increasing global climatic change, these should not be undervalued in regions where salt lakes are close to institutions. Microecosystems derived from salt lakes also have the potential to play a most important role as teaching tools: their simplicity, ease of manipulation, and the wide range of experiments that can be undertaken using them are notable (Williams 1991).

Ecological and conservation values

Not least amongst the values of salt lakes, though the most difficult to measure, is their value as an integral part of the biosphere: their biological diversity and ecological processes cannot be excluded from global diversity and biospheric processes with any certainty that exclusion will not have profound repercussions. Changes in the nature of the Aral Sea referred to above are the most indicative evidence of this sort.

One important ecological value of salt lakes that should receive particular mention is their role as feeding, refuge and breeding sites for many migratory or nomadic bird species. The loss of certain salt lakes of value in this respect may pose very serious threats to the continued viability of the bird species in question. The Ramsar convention recognises this and many salt lakes have already been designated as 'Ramsar sites'. Designation carries with it an obligation on the part of the country in whose territory the site lies to prepare and implement management plans. For many sites, unfortunately, such management plans do not yet exist. The number of salt lakes designated as 'Ramsar sites' is significantly fewer than freshwater sites, but as the conservational values of salt lakes become recognised this imbalance will surely change. Perhaps this book will be important in this respect.

CHAPTER 5

MANAGEMENT ISSUES

5.1 INTRODUCTION

Three major areas of interest are involved with regard to the management of inland saline waters: (i) management issues associated with natural salt lakes; (ii) the management of solar salt fields; and (iii) the management of salt released into the natural environment following anthropogenic activities on catchments (secondary salinisation). It is convenient to deal with these areas separately since the issues involved with each are for the most part quite different.

5.2 MANAGEMENT ISSUES ASSOCIATED WITH NATURAL SALT LAKES

The major management issues relate to anthropogenic impacts and the effects of these. Overall, the impacts are significant, diverse, comprehensive and mostly irreversible. Almost without exception, they are adverse. In short, an important part of the biosphere has already been irreparably damaged. Thus, impacts have been many and of different sorts, of short or long-term duration, affected part of the biota or the whole ecosystem, and limited in extent or totally destructive. Effects reflect this diversity, but with a good deal of overlap; i.e. different impacts often have similar effects, especially those, the most ubiquitous, which cause increased salinity. Particular impacts are also often lake specific, but there are many global generalities.

Because of overlaps, and to limit unnecessary discussion, the following account considers both impacts and effects together. For convenient discussion, the impacts are considered as those which mainly (a) act upon the catchment or drainage basin, (b) involve diversions of inflows, (c) result in the addition of unnatural waste products or other pollutants, (d) directly affect the biota, (e) cause physical change to the nature of the lake basin, and (f) follow global climatic and associated changes (Williams, 1993a). Not discussed separately, though important, is human ignorance: the misperception that salt lakes have limited use and value, are expendable 'wastelands', and do not merit serious consideration as sites of conservation interest.

Catchment/drainage basin activities

All lakes reflect catchment events, and in this respect salt lakes are particularly sensitive because their catchments are frequently in semi-arid regions where habitats are environmentally fragile and respond quickly to perturbations. Two events of significance in the present context are grazing by wild and domesticated mammals, and more direct changes to the natural vegetation imposed by man.

The effects of grazing, particularly overgrazing, become manifest in changes to run-off patterns and increases in sediment loads in run-off. Important physical changes are the formation of animal tracks and breakage of protective surface crusts; both events lead to mobilization of surface particles and erosion.

Changes to the nature of catchment vegetation by more direct human activity have been equally if not more significant. The felling of deep-rooted natural vegetation (trees) and its replacement by shallow-rooted grasses and crops has frequently led to changes in local hydrology. These changes lead to changes in the salinity, composition and seasonality of run-off. Thus, groundwaters (often saline) may approach the surface and ultimately reach a level where capillary action alone causes it to reach the surface. In certain regions, such as central Asia, capillary action may begin when the water table is as low as 10 m below the ground. Evaporation then acts to increase salinity and subsequent run-off adds the saline water (or precipitated salts) to the local drainage terminus, that is, the lake. The result is that lake salinity increases. The phenomenon is usually referred to as secondary salinisation and is discussed in a little more detail below (section 5.4). Western Australia provides many examples of this phenomenon. Many previously freshwater lakes and rivers there now have elevated salinities. Clear evidence is to be seen in the dead stumps of trees both in and marginal to the lakes and in observed spatial and temporal patterns of salinity change in rivers draining cleared areas (e.g. the Blackwood River). Regions in south-eastern Australia are just as much at hazard. Many floodplain wetlands associated with the River Murray lie above rising saline groundwater and increased salinity poses a threat to the river as a whole (given that dryland rivers are an integrated system of the river itself and associated floodplain wetlands).

Overgrazing, vegetation clearance and salinisation frequently lead to severe erosion and overall 'desertification' (land degradation) in semi-arid catchments. Already, some 1-2.5 x 10^6 ha of the Aral Sea catchment is at hazard from this phenomenon, especially in the delta areas of the Amu and Syr-darya, and its catchment is far from unique in this respect.

It should also be recognised, as Stine (1991) has stressed, that a lake and its catchment are closely linked geomorphologically, so that a change in the lake can instigate secondary changes in the lake catchment. Thus, at Mono Lake, California, the fall in water-level has forced the main inflowing streams to incise as much as 10 m. This incision, in turn, has resulted in a fall in the water-table over a considerable area with the consequential loss of many wetlands in the catchment. Stine also noted that there are critical levels for geomorphological impact (akin to critical biological levels, for example, in salinity). These critical geomorphological levels may represent threshold levels which, once passed, do not permit the restoration of original conditions should transgression (rather than regression) occur.

Diversion of inflows

Very large salt lakes frequently have more or less continuous inputs of fresh water. As indicated, this has long been recognised as a useful resource and considerable use of it has been made. As long as this use was of limited extent, no major impact upon the hydrological budget of the salt lake occurred. With increasing use, especially following the growth of human populations in semi-arid regions, major impacts followed. Some important lakes in this context are the Aral Sea and Lake Balkhash in central Asia, Lop Nor in China, and Pyramid and Mono lakes in the USA. Diverted water is used for a variety of purposes but irrigation is often an important use.

A special case involving water diversion is provided by Kara-Bogaz-Gol Lake in Turkmenia. This was a large salt lake connected to the Caspian Sea by a narrow channel (Fig. 6.2). Formerly, significant quantities of water flowed from the moderately saline Caspian Sea into the lake where it evaporated to create a large and highly saline water-body. When the water-level of the Caspian was at a low level, an essentially 'blind' dam was built across the entrance to the Kara-Bogaz-Gol. Subsequently, the lake more or less disappeared. Following the expression of some concern on this matter and especially following rising water-levels in the Caspian, some water was and is now flowing into the lake, but the 'reconstituted' lake is smaller and different from the old one (see also section 6.2).

The diversion of water by direct drainage has also led to the disappearance of many interesting salt lakes. This is particularly so in agricultural areas, as for example, the Seewinkel pans in Austria and pans in the Coto Doñana, Spain. Others have been destroyed by the excessive diversion (extraction) of underground water. The 'axalapazcos' of the Mexican plateau, whose existence largely depends or depended upon the existence of underground supplies, provide cases in point (Alcocer and Escobar, 1990).

Conversely, in some inland situations, water diversion may also give rise to salt lakes - though in the main such salt-water bodies are far from natural. The most notable example is the Salton Sea in California. This was created when the Colorado River broke the banks of a man-made channel in 1905 and flooded a large depression in southern California. The salinity of the lake has increased since 1905 and it now contains many introduced marine species, including barnacles.

The primary effects of significant water diversion from salt lakes upon the lakes are obvious and two-fold: water volume decreases and salinity increases. Each has many consequential effects.

The decrease in volume is accompanied by a decrease in lake area, especially in shallow lakes, and this in turn may expose large areas of the former lake bed. Sometimes a significant transfer of salt and sediment particles from the bed to surrounding parts of the drainage basin occurs. Lower lake levels may also cause the destruction of shallow and deltaic areas which may have provided important refuge areas and otherwise have been of conservation significance. Lowered water-levels may lead to the destruction of islands which formerly served to protect breeding populations from terrestrial predators, and to the emergence of submerged objects such as the tufa at Mono Lake, California (see section 6.6). In the Aral Sea, where extensive areas of the former lake bed now lie exposed, regional climatic change and an incidence in the frequency of dust storms have been attributed to the decreased area and volume of the lake and the increased area of exposed lake-bed (see section 6.2).

Increases in salinity lead to several chemical, physical and biological changes. Thus, increased salinity values may exceed the solubility products of certain dissolved salts leading to their precipitation and thus an alteration in the ionic composition of the remaining solution. Increased salinities also cause decreases in oxygen solubility. Increased densities may lead to changes in many physical phenomena, including seasonal patterns of thermal (and chemical) stratification (which are also influenced by decreased depths). More obvious perhaps than physico-chemical changes are changes in the composition of the biota. Whilst the importance of salinity as a direct determinant of the biota of highly saline lakes may not be large (see Williams, in press b), good correlations exist between salinity and species composition, richness and diversity in moderately saline lakes. Thus, as the salinity tolerances of species are exceeded, they are replaced by more tolerant species until the tolerance of these too is exceeded.

Pollution

The fact that salt lakes are the termini of closed hydrological systems has not prevented the discharge of a wide variety of pollutants to rivers flowing into them or to the lakes directly when it has been economically expedient to do so. Mostly, loadings relate more to criteria designed to protect open, freshwater systems. Thus, pollutant concentrations in salt lakes often reflect progressive accumulation (Williams, 1981).

Almost the whole range of pollutants discharged to fresh waters is also discharged to salt lakes or their inflows. Little point is served by giving details, but a few examples will illustrate the general statement. Lake Colongulac, Victoria, Australia, receives the effluent from a sewage plant located on its bank, and adjacent salt lakes receive nutrients in agricultural run-off (see section 6.5). High concentrations of certain metals occur in some Bolivian salt lakes near which mining occurs. Lake Maryut, Egypt, has high concentrations of tin in its sediments. High concentrations of organochloride residues are found in at least some of Kenya's rift valley lakes. And many salt lakes are used as dumps for domestic and other garbage.

There can be little doubt that the effect of these pollutants on salt lakes is essentially the same as it is on fresh waters - though the actual evidence is thin: additional nutrients promote algal growth, high organic loadings decrease diversity but increase biomass, and poisons decrease both diversity and biomass. The modifying effects of salinity have yet to be determined fully but they undoubtedly decrease diversity.

Direct impacts on the biota

In some salt lakes, the fauna is largely the result of purposive or serendipitous introductions. The Aral and Salton Seas provide the most notable examples. In many more examples, individual components of the fauna have been introduced. Thus, fish have been introduced in several moderately saline Canadian and Bolivian lakes. Fish have also been introduced into some moderately saline Australian lakes where they cannot breed but where populations are maintained by stocking. Not all attempts to introduce fish into saline lakes have proved successful. Of introduced invertebrates, various species and subspecies of *Artemia* have been spread worldwide. In the main, initial introductions were confined to coastal solar salt fields. There have been no attempts to control these largely *ad hoc* introductions either individually or at the governmental level despite the danger they pose to the regional genetic diversity of *Artemia* and the value of this. Geddes & Williams (1987) and Sorgeloos et al., (1987) have drawn attention to the danger of these introductions. Persoone & Sorgeloos (1980), amongst others, had earlier pleaded for the conservation of all remaining natural habitats containing *Artemia*.

Leaving aside introductions, direct impacts on faunal species are few. However, exploitation of flamingo populations, either to provide meat or eggs, poses a direct threat to the survival of some South American species.

Physical impacts on lake basins

Salt lake sediments, as noted, frequently contain minerals of commercial value (e.g. salt, soda, lithium, zeolites) and the mining of these frequently either physically changes the natural structure or appearance of the lake basin and/or indirectly leads to long-term changes in lake chemistry (and consequential biological effects). The derivation of useful salts from brines may also lead to physical change: often, this takes the form of dividing the basin into separate regions using low banks or levees separating waters of different salinity. Dredging activities may lead to the physical damage of some basins, as for example in the Caspian Sea.

In some cases, the mining of minerals beneath the lake bed or nearby may lead to a physical change in the basin. Thus, in Western Australia, mineral extraction from beneath some lakes has led to the construction of large in-lake mining 'voids' or quarries (from which saline groundwater needs to be pumped - so creating secondary effects). Also important are the construction of extensive rock causeways over the lake bed enabling transport to and from mine sites (Fig. 5.1). These causeways are usually not removed after mining has ceased. Apart from their obvious aesthetic impact, other impacts from these causeways remain unknown. Sometimes, excavated material is used to build artificial 'islands' on the lake bed. In other cases, mine waste is stored in dumps at the edge of the lake (and from which heavy metals and other pollutants may leach into the lake, especially when dumps are not properly maintained; Fig. 5.2).

Climatic and atmospheric changes

Finally, brief reference is made to possible changes in global climatic patterns and the ozone concentration in the upper atmosphere. Because salt lakes represent a sensitive balance between many climatic parameters (e.g. evaporation, rainfall, temperature), relatively small changes in these will cause large changes to the natural character of salt lakes. This has already been recognised by workers in Canada (Hammer, 1990).

The effects of climatic change could take various forms. Rising sea-levels would flood many coastally located athalassic salt lakes. Particularly in danger in this respect are the many athalassic saline lakes occurring on small oceanic islands. Increased aridity would lead to increased average salinities and ultimately to desiccation. Increased rainfall would lead to decreased average salinities and in extreme cases to the conversion of closed to open drainage systems.

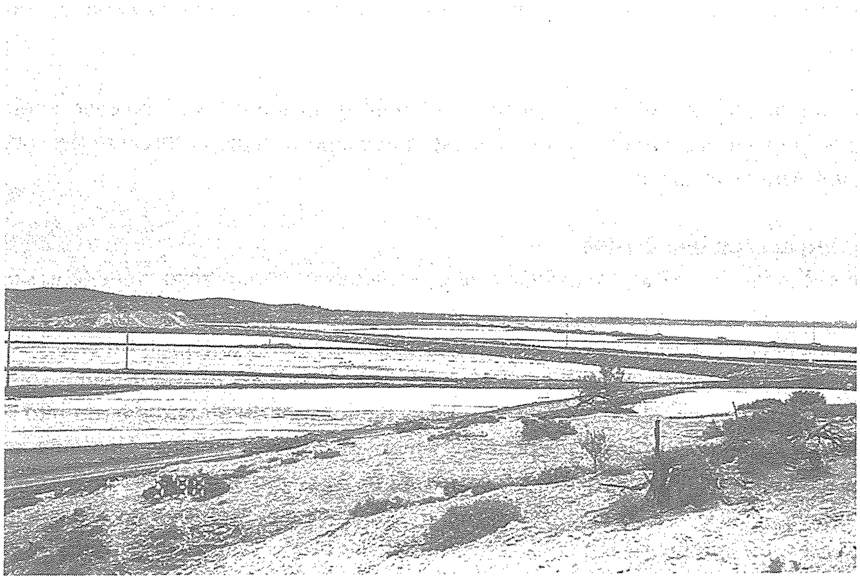

Fig. 5.1 Rock causeways on Lake Lefroy, Western Australia, enabling vehicular transport across the dry lake bed.

Fig. 5.2 Mine waste dump at edge of Pernatty Lagoon, South Australia. Run-off from the badly maintained dump can be seen in the foreground. The lake is in the background.

Changes to the seasonal patterning of climatic events would also lead to fundamental ecological changes. A major feature of this potential problem is that climatic changes are likely to occur, it is claimed, too rapidly to permit the biota of salt lakes fully to adapt naturally to them. On the other hand, it is possible that previous natural climatic changes have also been too rapid to permit tandem evolution. Certainly, there is evidence that some past climatic changes have been rapid, and many geologists believe that some significant global environmental changes occurred over relatively short periods (up to a few thousand years).

The problem with decreased ozone concentrations in the atmosphere is that these allow more ultra-violet radiation to reach the surface of salt lakes and excessive exposure to such radiation is deleterious to living tissues. The plankton of lakes cannot stand increased exposure for any length of time, but in deep lakes avoidance is possible by sinking to lower depths. This, of course, is not possible in shallow lakes. Since many salt lakes are shallow and already receive large amounts of ultra-violet radiation, the hazard is obvious.

Management measures

Against the many and different sorts of impacts sustained or faced by natural salt lakes, management must employ an equally wide variety of countermeasures. Many of these are similar to those applicable to freshwater lakes. The problem, however, is that such measures when applied to salt lake management do not fully take account of the many distinctive features of salt lakes and consequently are less than fully effective. A key feature in this respect is the closed hydrological nature of salt lakes. Thus, critical loading factors for plant nutrients, for example, derived from and designed to protect freshwater, open hydrological systems are not directly applicable in the protection of saline, closed hydrological systems. Much has also to be discovered about how salinity affects the biological activity of pollutants or to what extent and how it determines the structure of biological communities. The inherent physico-chemical and hydrological variability of many salt lakes provides for further difficulties in their management. Indeed, the lack of recognition of this key feature is the root cause of many failed management endeavours in salt lakes.

Notwithstanding the many distinctions between fresh and saline waters, the general approach to the effective management of both is the same: clear recognition of values; preventative measures against events likely to reduce these values (i.e. prophylaxis); constant monitoring of key indicators; and, when needed, remedial action.

5.3 MANAGEMENT OF SOLAR SALT FIELDS

Salt (NaCl) is a major component of many modern industrial processes, particularly the manufacture of chlorine and caustic soda ash. World salt production is now about 200 million tonnes each year. The enormous amount of salt required comes from mineral sources (rock salt) by mining or other ways, or from the ocean or underground saline water by solar evaporation. Those countries in warm regions near the sea often obtain most of their salt by solar evaporation of sea-water. In some countries, salt is harvested from natural salt lakes by scraping it from the bed of the lake when this is dry. Often, major physical changes are made to the lake bed to facilitate management, e.g. the building of long levees.

The overall management of solar salt ponds has changed little since historical times, but greater knowledge of chemical reactions and the importance of biological factors has increased efficiency and product purity. In modern operations, four series of ponds are involved: preliminary ponds where most water is evaporated and calcium carbonate precipitates; intermediate ponds where calcium sulphate precipitates; crystallising ponds where most sodium chloride is deposited; and final ponds (bitterns) where the highly soluble sulphates and chlorides of magnesium and potassium drop out. Fig 5.3 shows the sequence. Fig. 5.4 illustrates the disposition of ponds in a large facility in Western Australia. The basic sequence of mineral deposition when sea-water evaporates was carefully described over a century ago by Usiglio, and repetition has confirmed his description (Clarke, 1920). Details of a more modern analysis (Bassegio, 1974) are given in Table 5.1. These details are reproduced here because they are of considerable interest given the many ecological similarities of ponds in solar salt fields and natural lakes and they are not easily accessible in the ecological literature. Less need be written about salt production from inland salt lakes and pumped saline groundwaters. In both cases, evaporative sequences and procedures depend upon the composition of the original brine. If this is predominantly sodium chloride, the technology is often simple.

Many specific management issues are involved in the production of salt from solar salt ponds, varying from those of an essentially engineering sort (e.g. siting of ponds, pond maintenance, harvesting and washing of salt, strength of pond floors), through physico-chemical issues (e.g brine viscosity, density and transparency, control of appropriate flows through the field to maintain salt quality), to biological ones (e.g. the maintenance of a balance between algal growth and grazers, the promotion of bottom microbial mats to seal pond bottoms and prevent seepage, and the minimization of dissolved organic matter). Many of these issues are linked. Whatever the case, the central aim of the solar salt pond manager is to maximize salt quantity and quality. In attempting to do this, the manager must frequently address a variety of issues, some conflicting, such as the production of brine shrimp for aquacultural use (see section 4.2). Brine shrimp produced from solar salt ponds are essentially by-products for the most part.

None of the issues can be discussed here in any depth. However, note that many practical issues are addressed by Mannar and Bradley (1983) with particular regard to such issues in developing countries. Many issues are also addressed - though in individual papers - within the proceedings of a series of international symposia on all aspects of salt production (see, for example, Kakihana et al., 1993). The biological management of solar ponds has been discussed *inter alia* by Davis (1993), Burnard and Tyler (1993), Coleman and White (1993), and Davis and Giordano (1996); microbial mats have been discussed by Jones et al., (1981), Taher et al., (1995) and Roux (1996); and brine transparency, colour, and the nature of the microbial communities in the water column have been considered by Oren et al., (1992), Oren (1994), and Oren and Dubinsky (1994). Whilst the management of the biological communities of salt ponds can affect the amount of salt harvested (e.g. by decreasing evaporation), the major impact of the biota is on salt quality. Salt quality is also affected, and to a more significant degree, by several non-biological phenomena. It is of some interest therefore to discuss this matter in a little more detail.

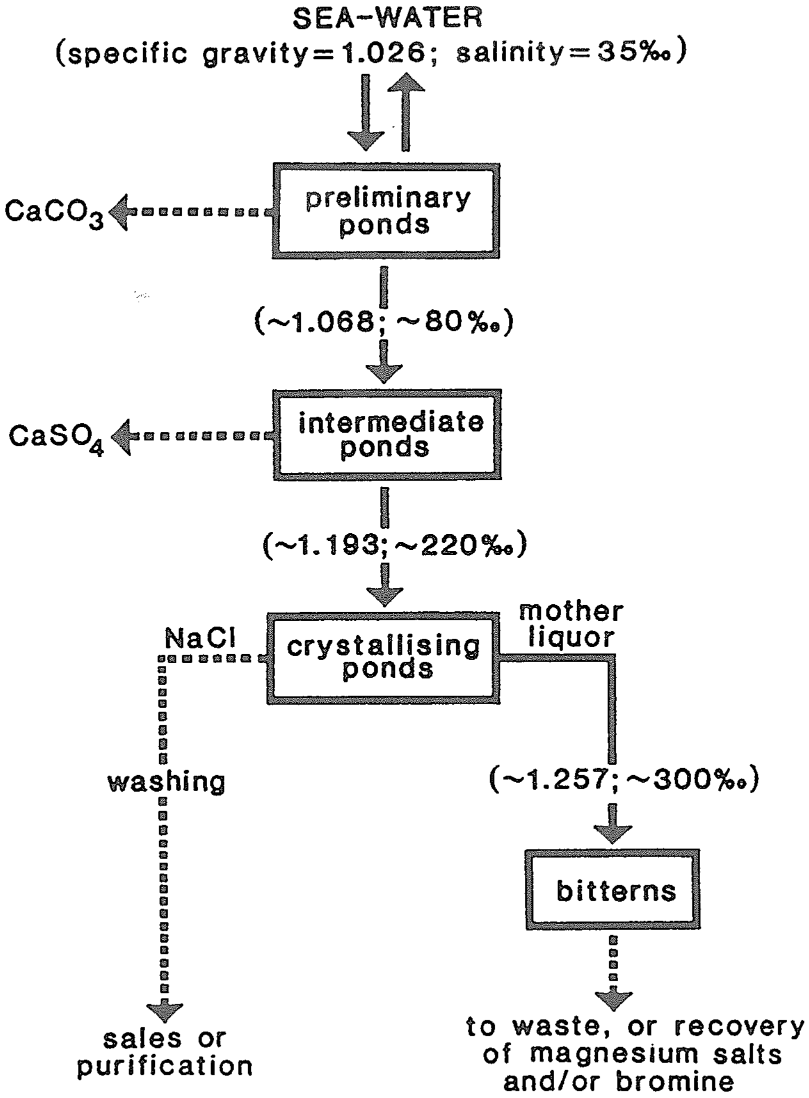

Fig. 5.3 Schematic production sequence in a coastal solar salt field.

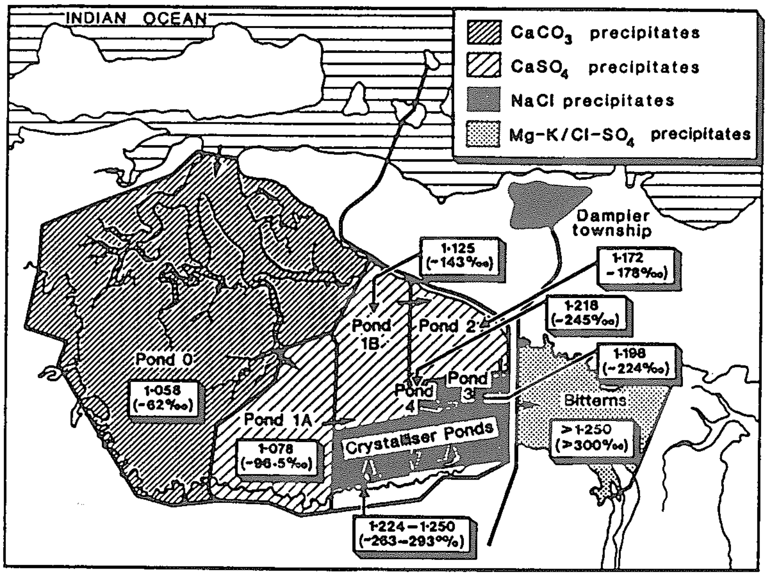

Fig. 5.4 Pond disposition in a solar salt field at Dampier, Western Australia. Redrawn after Sammy (1983).

Table 5.1 Salts (g/L) from evaporated seawater as a function of brine density ($D^{22.2}$) at 22.2 °C. Data from Bassegio (1974).

Specific gravity	°Bé	$CaSO_4$	$MgSO_4$	$MgCl_2$	NaCl	KCl	NaBr	Total salts
1.0247[1]	3.5	1.419	2.138	3.384	27.27	0.741	0.085	35.04
1.0500	6.91	2.816	4.367	6.719	54.98	1.491	0.172	70.56
1.0897[2]	11.94	5.048	8.096	12.04	99.92	2.709	0.313	128.33
1.1000	13.18	4.695	9.197	13.60	113.08	3.062	0.354	144.00
1.1500	18.91	3.171	14.58	21.19	179.09	4.807	0.555	222.06
1.2000	24.17	1.862	20.03	29.18	243.81	6.588	0.760	302.05
1.2185[3]	26.00	1.400	22.06	32.28	268.38	7.266	0.840	332.29
1.2450[4]	28.53	0.703	57.11	83.42	193.20	18.710	2.160	355.38
1.2500	29.00	0.595	63.24	92.71	180.34	20.760	2.390	360.15

1. Open ocean seawater.
2. Density at which $CaSO_4.2H_2O$ begins to precipitate (assuming little or no carbonate present).
3. Density at which NaCl begins to precipitate.
4. Density at which bitterns are discarded.

Several criteria are used in determining salt quality. The quality of industrial salt is determined by the size, shape, specific gravity, percentage moisture, and Ca, Mg and SO_4 contamination of salt crystals. Salt of high quality has large crystals, solid and cubical in shape, a density of 2.16, a low moisture content, and lacks significant amounts of impurities (i.e. organic matter, final brine gypsum and other inorganic compounds). Salt crystals (NaCl) grown slowly from pure solution are of the highest quality. Quality may be decreased in several ways: by fast and interrupted growth, by sudden changes in local conditions, by adsorption of impurities, or by temporal or concentration gradients in the crystallizer. Fluctuations in temperature or salinity may cause the decomposition of smooth layers and their transformation into rough surfaces which may grow too quickly and lead to the formation of macro defects. Crystals grown from impure solutions are often dendritic in shape with 5-30% inclusions, or microporous with a good central nucleus surrounded by pitted layers of irregular growth. Polysaccharides in solution and derived from *Synechococcus*, a common blue-green alga of solar salt ponds, can change the morphology of salt crystals from a solid cuboidal form to a hollow, skeletal 'hopper' shape (Ghassamzadeh et al., in press). Such 'hopper' shaped crystals have a lower density than purer salt crystals. Hollow crystals may also entrap polysaccharides, gypsum and final brine, leading to an increase in moisture content and impurities.

5.4 MANAGEMENT OF SALT RELEASED BY SECONDARY SALINISATION

In many semi-arid regions, the growth of crops depends on the application of an artificially derived supply of water, i.e. irrigation. The water mostly comes from dryland rivers (some terminating in salt lakes), either directly or after impoundment. Apart from the effects that the abstraction of water has upon the natural environments from which it has been derived, irrigation itself often leads to adverse environmental effects, especially the phenomenon of secondary salinisation (sometimes referred to as mineralisation), that is, the development of an anthropogenically induced and unnaturally high salinity in surface waters or terrestrial environments (Ghassemi et al., 1995).

Secondary salinisation can originate in various ways. One involves rising saline or near saline groundwater levels following downward percolation of excess irrigation water. Once the groundwater nears the surface, capillary action causes an upward movement of water and the deposition of salt after surface evaporation. Salt deposits subsequently wash into local surface waters.

Secondary salinisation also occurs outside irrigation areas. There, the principal cause is the removal of deep-rooted vegetation and its replacement with shallow-rooted species. The decrease in water transpired from the landscape has the same effect on groundwater levels as the addition of excess irrigation water. They rise and lead to the deposition of surface salt after evaporation.

An inability to manage irrigation properly so as to avoid secondary salinisation and salt damage to crops was probably a contributing factor in the demise of one of the earliest of human civilizations, the Sumerians, who lived and farmed on the floodplains of the Tigris and Euphrates in Mesopotamia. Modern agricultural practices endeavour to minimize secondary salinisation and salt damage to crops, but even so irrigation frequently results in the production of saline waste water needing disposal (either from surface drainage or from pumping to maintain groundwater at low levels). This waste water is disposed of in various ways. Sometimes it is discharged into nearby rivers when these are flowing strongly. Sometimes it is discharged into local depressions (often the dry basins of temporary wetlands). The management of these discharges (where, when, for how long, and how much) often leaves much to be desired from an environmental impact point of view.

A frequent method of disposal is to discharge saline waste water into so-called evaporation basins, either natural wetlands or constructed basins. Evaporation basins are common on the Murray River floodplain of Australia and in California (e.g. Evans, 1989; Chilcott et al., 1990; Williams, in press) but are not confined to these areas. Although effective as a short-term, expedient management technique, their longer-term value is questionable. More immediate concerns about those in California include concerns about their accumulation of certain elements (selenium) which are toxic to wildlife, especially birds. Even when no immediate concerns exist, it should unequivocally be stated that evaporation basins are quite unlike natural salt lakes and have lower environmental values despite reports suggesting otherwise (e.g. Roberts, 1995). Not the least of the differences are those involving seasonal hydrological and salinity patterns, both important environmental determinants. Again, the management of evaporation basins to minimize environmental impacts needs improvement.

Where saline waste water is not effectively managed (or more directly stated, where either irrigated or dryland farming is allowed without adequate management procedures or controls in place to deal with saline waste waters), the addition of salinized water to groundwaters, rivers and lakes inevitably results in adverse environmental impacts (Williams, 1987). The extent of this problem has not been fully recognized, it has not been adequately resolved, and the environmental price will be heavy. Scientists are only now beginning to be aware of the extent of the problem. In South Africa, for example, Davies and Day (1998: 187) recently noted that "salinisation of rivers is [now] recognized as one of the major threats to South Africa's water resources. Indeed, the water quality of many South African rivers ... is rapidly declining as a result of irrigation-induced salinisation."

CHAPTER 6

CASE STUDIES

6.1 INTRODUCTION

This chapter discusses a small number of particular salt lakes to give substance to the general remarks of preceding chapters. In selecting lakes for discussion, consideration was given to geographical position, size and importance, the extent of knowledge, and the degree to which they illustrate the variety of salt lakes, the nature of impacts and their effects, and management and conservation issues. Those selected are the Caspian and Aral Seas, Qinghai Hu, the Dead Sea, Lake Corangamite, Mono Lake and Mar Chiquita. Thus, examples are given of lakes in central Asia, the Far East, the Middle East, Australia, and North and South America. Some of the lakes are extremely large (the Caspian, >400,000 km^2) and some relatively small (Corangamite, 252 km^2), highly saline (Dead Sea, salinity, 340 g/L) or moderately saline (Caspian, ~12.5 g/L), some about which a good deal is known (Mono Lake) and some about which little is known (Mar Chiquita), and some subject to significant anthropogenic impact (most, but especially the Aral Sea) and some subject to little (Qinghai). Finally, the lakes selected include examples which have attracted much attention from water resource managers and conservationists (e.g. Mono Lake) and others which have not (Qinghai).

This selection does *not* adequately represent the variety of salt lakes that exists; it does not, for example, cover temporary salt lakes (either episodic or intermittent), nor are there any examples of African salt lakes (of which many are of great scientific and other interest). Also excluded are examples of solar salt pans, evaporation basins and heliothermal ponds. Selection has given emphasis to those lakes which are large, permanent, regionally important, and have high economic, scientific, conservation or other values of management interest. The thrust of the chapter is to exemplify issues.

In dealing with each lake, a brief description is given of location and major physico-chemical and biological features. Principal values and threats or impacts to the lakes are indicated. The effects of impacts are outlined as well as measures to mitigate them (if any). Finally, a prognosis for each lake is provided.

All of the lakes selected, for whatever reason, exemplify the key limnological feature distinguishing salt lakes from freshwater ones: the much more sensitive response of salt lakes to changes in water budgets, irrespective of whether these changes originate from anthropogenic activities or are the result of climatic perturbations. All of the selected lakes have recently and are presently undergoing change to a degree not usually experienced by freshwater lakes within the same time frame. Thus, like most large, permanent salt lakes worldwide, the Aral Sea, Qinghai, the Dead Sea, Mono Lake and Lake Corangamite have recently undergone significant falls in water-level (with concomitant rises in salinity and changes in ecological conditions). In Mar Chiquita and the Caspian Sea, on the other hand, water-levels are rising and salinities falling. All changes are of great regional interest and concern, but their global extent seems not to have caught the attention of limnologists to the degree that could reasonably be expected, particularly those - the most common - with falling water-levels (Williams, 1993b, 1996b).

6.2 THE CASPIAN AND ARAL SEAS

The Caspian and Aral Seas are two extremely large lakes in central Asia (Fig. 6.1). The former is by far the largest lake in the world, and the latter was the fourth largest before its recent regression beginning 1960. Despite their relative proximity and similarity of geographical position, they differ in many features, including origins, biology and hydrological behaviour. Despite these differences, they are considered together here because this will serve to highlight an important feature so far as the management of salt lakes is concerned: the often remarkably different responses shown by even relatively close salt lakes following natural or anthropogenically induced changes, particularly those involving water budgets. It follows that salt lakes require much more sensitive hydrological management than freshwater lakes.

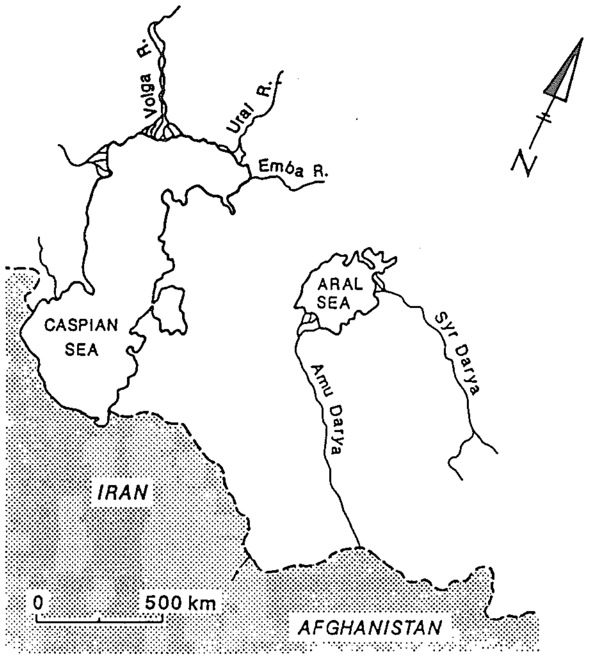

Fig. 6.1 Position of Caspian and Aral Seas in central Asia.

Table 6.1 Major morphometric features of the Caspian and Aral Seas. Caspian data after Shayegan and Badakhshaan (1996); Aral Sea data after Williams and Aladin (1991) and applicable to the situation in 1960.

	Caspian	Aral
Surface area (km^2)	429,140	68,000
Volume (km^3)	78,000	1,090
Maximum length (km)	1,160	390
Maximum width (km)	448	280
Maximum depth (m)	26[1] 958[2] 960[3]	69
Mean depth (m)	6[1] 200[2] 300[3]	16.0
Shoreline length (km)	5,200	n.a.

[1] Northern basin
[2] Central basin
[3] Southern basin

Table 6.1 documents that major morphometric features of the two lakes and Figs 6.2 and 6.3 illustrate their bathymetry. These features have undergone and are undergoing considerable change as volumes of water in the lakes change in accord with changes in the water budget of each. The most obvious feature reflecting this is water-level. This is plotted in Fig. 6.4. From this, it can be seen that water-levels were more or less constant in the Caspian from about 1830 until about 1929, from 1929 to 1977 fell, but have since risen gradually. In the Aral Sea, on the other hand, water-levels were quasi-stable until 1960 but since then have consistently fallen and continue to do so. If the fall continues, as will almost certainly be the case, the water-level in the Aral Sea will have fallen over 20 m from its 1960 level.

The major ionic composition of the two lakes is similar (Table 6.2), but salinities differ. In the Caspian Sea it is about 12.7 g/L, and because of the large volume of the lake has shown little change as water-levels change. This is not the case for the Aral Sea. From a quasi-stable salinity of ~10 g/L before 1960, salinities have risen in the main basin to near 35 g/L and are expected to continue to rise (to >60 g/L by 2000).

The biology of the two lakes is not the same and this reflects their different origins. The Caspian is an ancient (end of Pliocene), cut-off remnant of a much larger marine body; the Aral has never had any marine connections and arose somewhat later (<3 × 10^6 years ago). As a result, the Caspian has a diverse biota of which a significant proportion comprises Tertiary relicts (~400 species). The Aral, on the other hand, has an impoverished biota of which few, if any, are endemic. Attempts have been made to 'improve' the biota of both lakes by introducing species from elsewhere. The intentions were to increase the productivity of the lakes for the benefit of fisheries. These attempts have significantly changed the Aral biota (Aladin et al., in press).

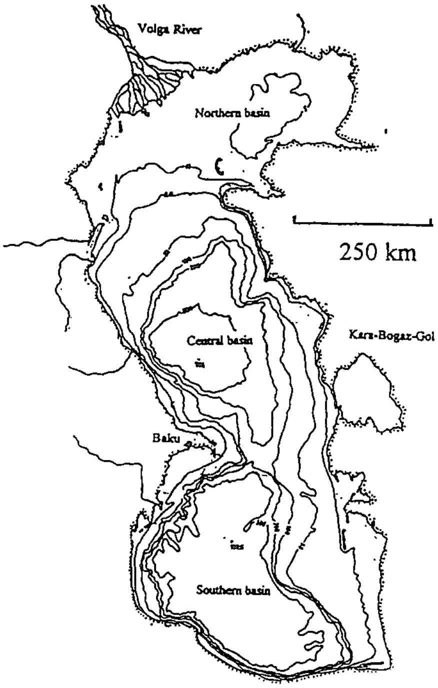

Fig. 6.2 Bathymetry of Caspian Sea. After various authors.

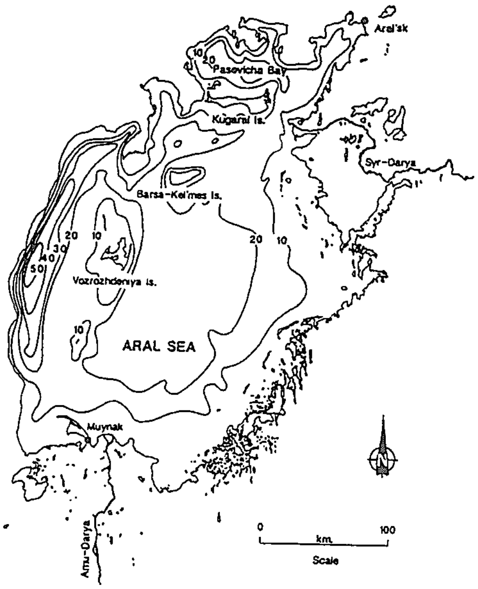

Fig. 6.3 Bathymetry of Aral Sea prior to 1960. After various authors.

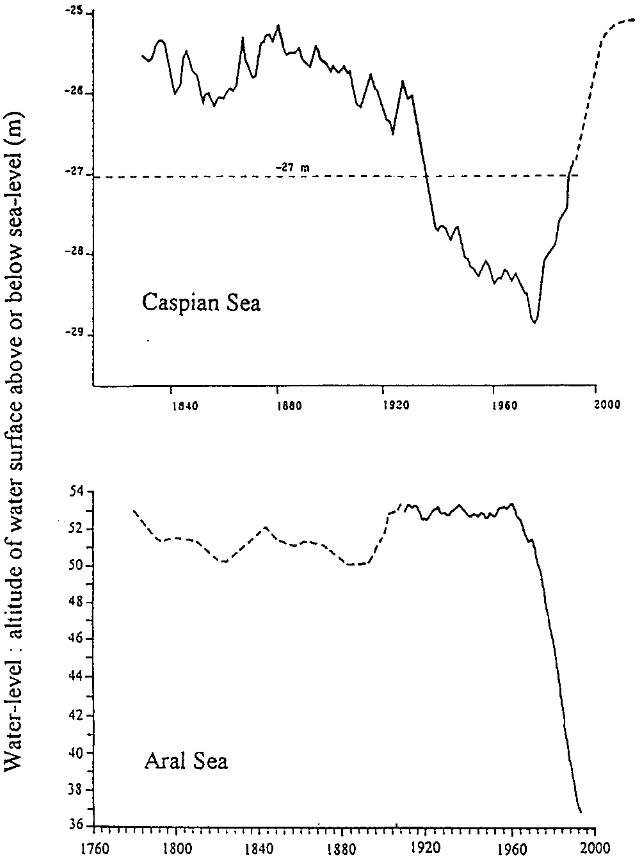

Fig. 6.4 Changing water-levels in the Caspian and Aral Seas. After various authors.

Table 6.2 Major ionic composition of the Caspian and Aral Seas. All data as g/L. Data on Caspian after Kosarev and Yablonskaya (1994); data on Aral from Williams and Aladin (1991) after various authors and applicable to the situation in 1960.

Ion	Caspian	Aral
Na	3.2	2.2
K	0.1	0.1
Ca	0.3	0.5
Mg	0.7	0.6
Cl	5.3	3.5
SO_4	3.0	3.2
$HCO_3 + CO_3$	0.1	0.2
Salinity	12.7	10.3

According to Kasymov (1987), the Caspian has a more or less stable biota of some 1,500 species of which the most notable are the Caspian seal (*Phoca caspia*) and sturgeons (Acipenseridae). The biota of the Aral is much less stable and even in the quasi-stable period before 1960 comprised about 600 species. There are many fewer now.

The values of the Caspian and Aral Seas are numerous, but many have been seriously degraded. Formerly, both were important for fishing, with the Caspian producing about 90% of the world's catch of sturgeons. Fishing is still important in the Caspian, with most of the catch coming from the northern part. Whilst total amounts caught have fluctuated widely, in the period 1976-1980, the total catch weighed 50,000 tonnes annually. The value of the fishery in the Aral was somewhat lower, but not inconsiderable.

Another economic value of the Caspian Sea was as a source of salts. These were formerly harvested by a chemical extraction plant at the side of an extremely large eastern embayment, the Kara-Bogaz-Gol (Fig. 6.2). Both lakes were useful for local transport between ports, the Caspian in particular. Finally, not the least of the economic values of both lakes was the value of the water in their inflows, the Volga in the case of the Caspian, and the Syr- and Amu-darya in the case of the Aral.

As for cultural values, both lakes figure prominently in the cultural history of mankind in general (both are close to some of the earliest of human civilizations) and central Asian communities in particular. As well, both are of considerable scientific interest. The diversity and endemicity of the biota of the Caspian and the responses of the Aral Sea biota to changing salinities are of notable interest. The conservation value of both lakes should also be mentioned. Wetlands on the Volga delta are of great importance to many migrating waterfowl as were the numerous kultuks (islands) in the south-east of the Aral Sea (now lost).

The most important anthropogenic impacts, especially on the Aral, have been the diversions of water from inflowing rivers. The falls in the water-level of the Caspian before 1977 were largely attributed to diversions, and the falls in the Aral are undoubtedly due to diversions. Other important impacts on the Caspian include the discharge of large amounts of pollutants (petroleum and associated products, phenols, pesticides and heavy metals) and the damming of the Kara-Bogaz-Gol Gulf.

The effects of these impacts have been far-reaching and varied. So far as the effects of diversion are concerned, these are most obvious in the Aral. Here, as water-levels fell following diversion, salinities rose, the biota changed and became less diverse, the fishery collapsed, islands in the south-east disappeared together with their values for conservation, large areas of the lake bed became exposed and salty particles from them blew landward so decreasing agricultural production and causing human health problems. The smaller size of the lake has also been blamed for giving rise to a more extreme climate (-50 °C to +50 °C represents the annual range in air temperature) and causing a greater frequency of dust storms. The impacts of the diversions on the Caspian contributed to the falls in water-levels, but these impacts were not as great nor their effects as significant as in the Aral. Even so, such was their effects and such was the concern about future falls that a dam was built across the entrance to the Kara-Bogaz-Gol to stop the loss of water from the Caspian to this embayment. As it subsequently turned out, these effects were reversed and the concern was misplaced: the Caspian began to rise. Now, rising levels threaten to flood (or have flooded) offshore oilfield infrastructures, onshore oil fields, oil and nuclear waste dumps, and coastal agro-industrial complexes, have destroyed roads and buildings, and have salinized coastal agricultural areas (Dumont, 1995). Much damage is also being done to areas of conservation value in the Volga delta. The exact reasons for the reversal in the nature of the water budget are not certain. Large-scale earth movements and decreased aridity have been suggested as possible causes.

Few if any effective management measures have been taken to mitigate the effects of the impacts. The Aral Sea has attracted most international attention in this regard and UNEP, the World Bank and NATO, to name just some international organizations interested in the problems of the lake and its environs, have all been involved in attempts to address or redress the problems (e.g. Anon., 1994, Micklin and Williams, 1996). So far, these attempts, at least for the lake itself, have had minimal impact. One management response, however, does seem to have had some success, albeit limited: a dam has been built across Berg's Strait, a narrow channel between the northern, smaller basin of the Aral Sea and the southern, larger one, and this has succeeded in retaining the reduced inflow of water from the Syr-darya in the northern basin. As a result, its water-level has increased and its salinity has decreased (Aladin et al., in press). Other much longer dams have been proposed for construction in the southern basin to cordon off parts of it (Glazovsky, 1995). Proposals to transfer water from the Caspian or elsewhere to the Aral, to increase local rainfall artificially, and to induce increased rates of glacier melting are essentially speculative and unlikely or impossible to be implemented. The only management measure likely to be effective for the Aral Sea in the long-term, at least to stabilize its current level if not to restore and rehabilitate it to its previous condition, is significant restructuring of agricultural and irrigation practices on its catchment to conserve water (Glazovsky, 1995). There seems little likelihood of this happening in the near future. What is likely, therefore, is that the main body of the Aral will continue to recede, its salinity to increase, and its biota to become less diverse. Most of the original values of the lake will disappear. The scenario predicted by several authors is shown in Fig. 6.5. As can be seen, the prediction is that both of the lakes into which the original lake has already divided will become considerably smaller.

Unlike the Aral, where the direction of change is clear and predictable, further changes in the water-level and other dependent features of the Caspian are neither clear nor predictable. At present, as indicated, and for the immediate future, water-levels are rising, but how long they will continue to do so and at what height they will stop is not known. In the meantime, management measures must largely take the form of flood protection and shore reinforcement actions (Kaplin, 1995). Additional measures proposed include diversion of lake waters to closed basins nearby.

Information on the two lakes is scattered, often inaccessible (particularly the older literature), and mostly in Russian. A key - though old still useful - reference in English is Zenkevitch

(1963). Recent non-Russian literature of interest includes: Micklin (1988), Kotlyakov (1991), Williams and Aladin (1991), Letolle and Mainguet (1993), Aladin and Williams (1993), Anon. (1994), Kosarev and Yablonskaya (1994), Anon. (1995), Dumont (1995), Glazovsky (1995), Kaplin (1995), Micklin and Williams (1996), Shayegan and Badakhshan (1996), Golubev (1996), and Aladin et al., (in press).

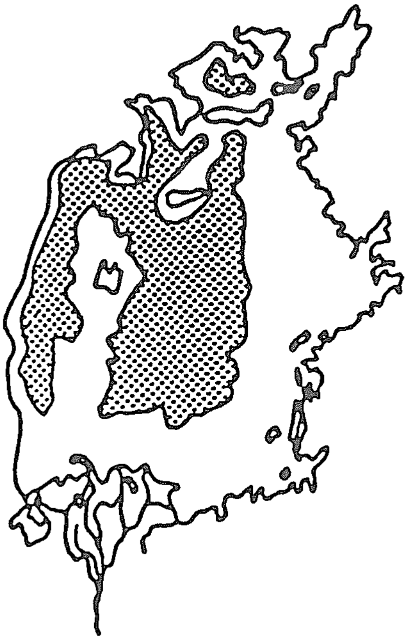

Fig. 6.5 Future shape of the Aral Sea in the next millenium. Solid line is the form of the lake prior to 1960; stippled areas are the future areas of the lakes. After Williams and Aladin (1991).

6.3 QINGHAI HU

Qinghai Hu (here, simply Qinghai) is the largest lake in China, and is located at high altitude (3,194 m asl) on the eastern margin of the Qinghai-Tibetan plateau (Fig. 6.6). In 1961-63 and 1990, its major morphometric features were as shown in Table 6.3. From the table, it can be seen that between these dates the lake had decreased in size. This decrease is part of a long-continued trend as shown by Fig. 6.7 which illustrates the decrease in water-level between 1955 and 1990. This decrease is not, however, of recent origin; anecdotal and historical information indicates that the lake has been regressing for several thousand years in accord with regional trends towards aridity. The first firm record was for 1884-86 when the lake surface stood at 3,207 m asl and its depth was ~39 m. By 1927, its level had fallen by about 2 m, and by 1990 a further 11 m. Palaeolimnological data (Chen Kezao et al., 1990) indicate that this regressive phase is only one of several that have occurred over geological time.

Data on salinity are less firm. The first acceptable value relates to the period 1961-63 when salinity was ~12.5 g/L Later values are 13.3 g/L for 1982 and 14.2 g/L in 1986. Salinities fell slightly after above average rainfall in 1989 but will undoubtedly continue to rise in the future. Most of the ions involved are Na and Cl (Table 6.4).

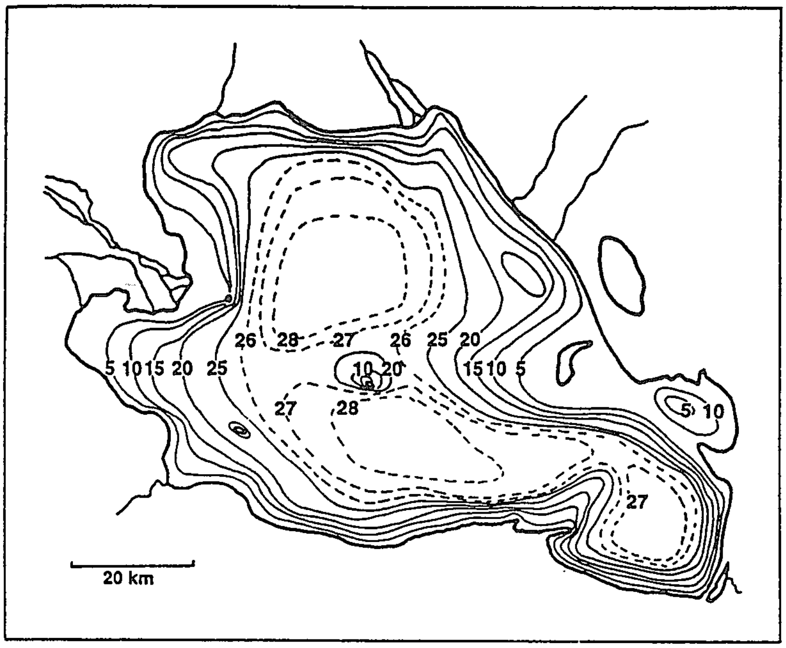

Fig. 6.6 Bathymetry of Qinghai Hu. After Academica Sinica (1979).

Table 6.3 Major morphometric features of Qinghai in 1961-63 and 1970. Data from Academica Sinica (1979) and after Walker et al., (1996).

	1961-63	1990
Surface area (km^2)	4,635	4,437
Volume (km^3)	85.4	84.4
Maximum length (km)	106	-
Maximum width (km)	63	-
Maximum depth (m)	28.7	26.9
Mean depth (m)	19.2	19.0
Shoreline length (km)	360	-

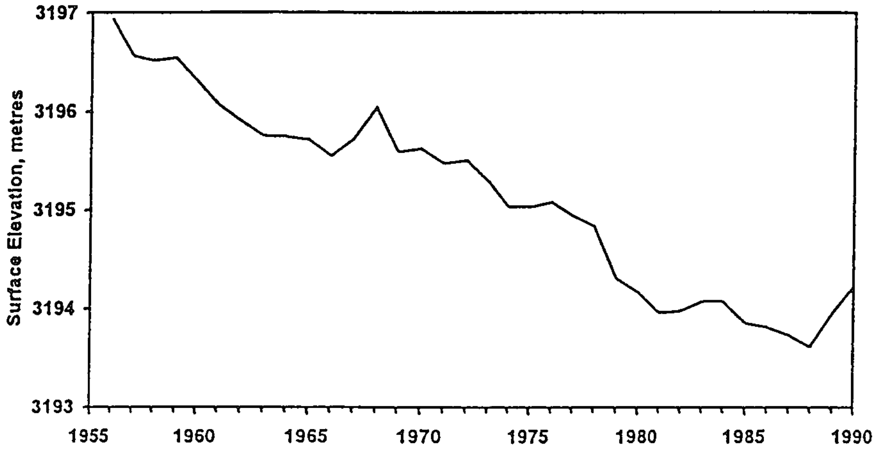

Fig. 6.7 Water-level of Qinghai between 1955 and 1990. After Walker et al., (1996).

Table 6.4 Major ion composition of Qinghai. All data as g/L. Data for 1962 from Academica Sinica (1979); data for 1986 after Walker et al., (1996).

Ion	1962	1986
Na	3.3	3.75
K	0.1	0.2
Ca	0.0	0.0
Mg	0.8	0.8
Cl	5.3	5.8
SO_4	2.0	2.4
$HCO_3 + CO_3$	0.9	1.2
Salinity	12.5	14.5

The biota is moderately diverse with some 17 species in the zooplankton, almost as many in the benthos, and some 35 phytoplankton species. In the zooplankton, *Arctodiaptomus, Moina, Brachionus, Hexarthra* and several protozoan taxa are important; the benthos appears dominated by chironomids. Mats of *Cladophora* cover the bottom in summer, and there are several littoral macrophyte species. Many bird species are either resident at the lake or use it as a feeding stopover during migration. There are five species of fish: four loaches and an endemic cyprinid, the naked carp (*Gymnocypris przewalskii*).

The two most important economic values of the lake are the value of its inflows as a source of irrigation water (diverted from three of the major inflows into the lake), and commercial fishing of the naked carp. Diverted water is used to irrigate barley and rafe during a short growing season. The commercial fishery makes a significant contribution to the diets of local people, especially the poorest. The fishery, though small, is robust. Annual catches have been highly variable but in 1992 were conservatively estimated at 3,000 tonnes. Illegal fishing probably also catches a considerable tonnage. Because of its halotolerance, the naked carp may be an important resource in another way: as a suitable species for transplanting to other moderately saline lakes in China.

Other values of the lake include its scientific interest, its conservation importance, its scenic attractiveness and its cultural significance. Palaeolimnologists, for example, have been greatly interested in the lake as a sensitive palaeoclimatic monitor of past events in Asia (e.g. Chen Kezao et al., 1990). Like Mono Lake (see below), it is an important feeding stopover for many migrant birds and its resident bird colonies have been promoted for tourism. Tourism was encouraged by the construction of hotels but now seems to be unimportant. Finally, for local Tibetans, the lake is culturally important: they believe that the spirits of the dead enter the bodies of the fish in the lake.

Major impacts on these values are essentially two-fold: water diversions from inflows, and regional trends towards increased aridity. Although diversions are not large, they remove about 5% of total inflows, with most from the Shalui River. The effects of the diversions, apart from those on the lake itself, include some on the spawning of the naked carp. The Shalui River, used by the naked carp for spawning when flowing, is now completely dry for part of the year. Other anthropogenic impacts are erosion of the catchment by stock and within water-courses. Eroded material gives rise to increased sediment loads with secondary adverse effects on the spawning areas of the naked carp. One potential impact should be mentioned: the proposal to introduce the rainbow trout. Investigations have already been made of its ability to live in Qinghai water. The rationale behind the proposal is that rainbow trout are more valuable than naked carp and can be exported from the province. It need hardly be added that the effect of the trout on the carp is likely to be adverse. The local people unable to afford trout would also be adversely affected.

Little is being done to address the effects of the impacts apart from some local erosion control measures. It seems likely then that water-levels will continue to fall slowly, salinities to rise gradually, and sedimentation to continue; the values of the lake will be degraded by attrition. Exactly when the increased salinity will be become intolerable to the naked carp is not known. The LD_{50} has been experimentally determined at 18.4 g/L, and so if the conservatively estimated annual rise in salinity is correct (0.05 g/L per year) the limits of tolerance will be reached in about a century. No doubt catches will fall before that limit is reached.

The two most comprehensive accounts of the lake of interest are those by Academica Sinica (1979) reporting on the results of a scientific expedition to the lake, and Walker et al., (1996). A more geographically comprehensive account of saline lakes on the Qinghai-Tibet Plateau is given by Zheng Mianping (1997).

6.4 THE DEAD SEA

The Dead Sea, the lowest lake on earth at just under 400 m below sea-level, is located in the Dead Sea-Jordan Rift Valley (Fig. 6.8) and is thought to be between 12,000 and 70,000 years old. Until its recent regression, the lake was divided into a large and deeper northern basin and a smaller, shallower southern one separated by a sill of about 3 m depth. At that time, its morphometric features were as indicated in Table 6.5. In past decades, however, diversions of water from the River Jordan have resulted in dramatic falls in water-level - some 15 m occurred in as many years - so that now only the northern basin exists as a natural lake. The southern basin remains only as a series of evaporation ponds for the production of minerals (and to maintain sites for those who visit the lake for therapeutic reasons). The fall in water-level between 1980 and 1991 is indicated in Fig. 6.9. The lake continues to regress.

Salinities, in accord with falling water-levels, have increased from a value of about 200 g/L in 1910 to 340 g/L. Little change in ionic composition has occurred, however; the cations remain dominated by Mg and Na, the anions by Cl (Table 6.6). A notable feature of the chemistry of the lake is the large amount of Br present. The northern basin is meromictic but overturned in 1979.

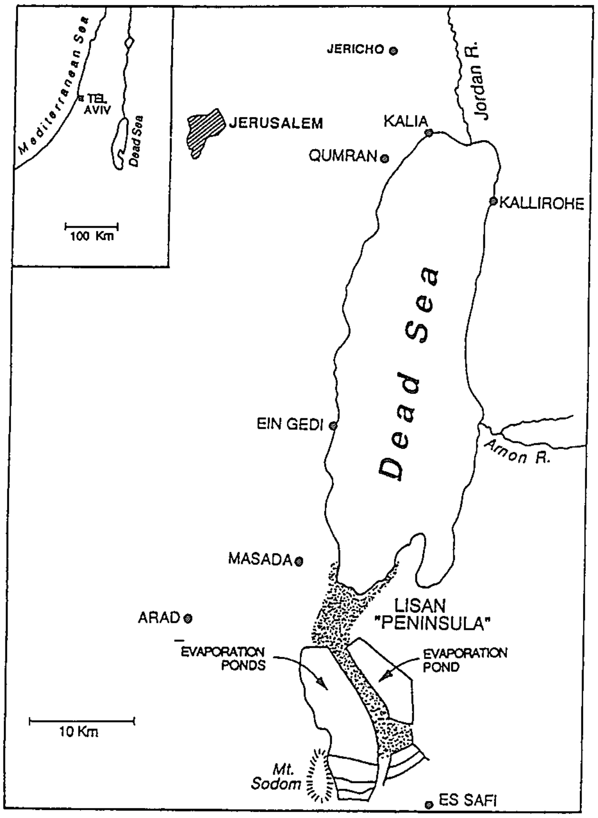

Fig. 6.8 Position and outline of the Dead Sea. After Nissenbaum (1993).

Table 6.5 Major morphometric features of the Dead Sea. After various authors.

Surface area (km^2)	940
Volume (km^3)	136
Maximum length (km)	65
Maximum width (km)	14
Maximum depth (m)	330
Mean depth (m)	144.7
Shoreline length (km)	~150

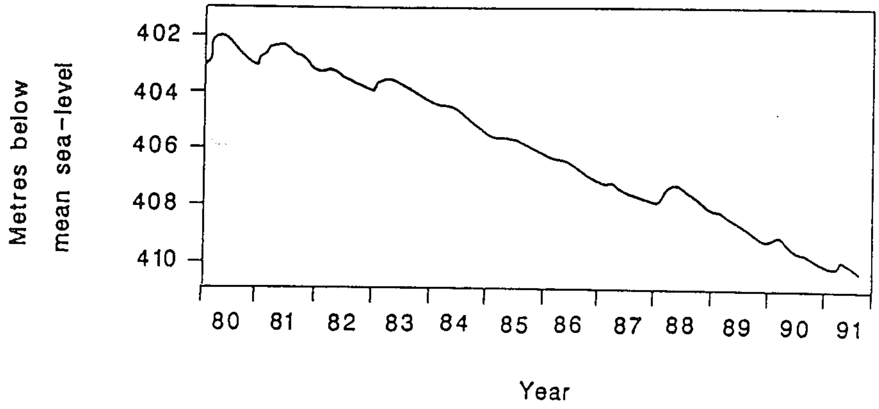

Fig. 6.9 Water-levels of the Dead Sea between 1980 and 1991. After Oren (1992).

Table 6.6 Major ion composition of the Dead Sea. Data as g/L. After Nissenbaum (1993).

Ion	
Na	40.1
K	7.7
Ca	17.2
Mg	44.0
Cl	224.9
Br	5.3
SO_4	0.5
HCO_3 + CO_3	0.1
Salinity	339.6

As for the biota, this is the least diverse of any of the case studies discussed here, or indeed of any salt lake; it almost entirely comprises Halobacteria and *Dunaliella parva* (a green alga). Notwithstanding its lack of biodiversity, the lake is certainly not 'dead'.

The lake has numerous non-economic values (see Nissenbaum, 1979, 1993 for an extended discussion). It has been of cultural significance to some of the world's most important religions for millenia. Its waters are claimed to have therapeutic properties, as attested to by a large southern resort which caters for those who visit for medical reasons. It is not without aesthetic appeal. And it is certainly of wide interest to many scientific disciplines.

Its economic values are considerable. Apart from the value of its diverted waters to the Israeli economy, it is a major international source of potash, bromine and magnesium. These are extracted by a chemical factory at the southern end of the lake. Other less important economic values include asphalt (of largely historical significance) and salt (halite).

By far the most important impact on the lake has been the diversion of waters from its inflow. The effect has been dramatic. Water-levels, as indicated, have fallen over 15 m, the southern basin has essentially dried up, large areas of the former lake bed have become exposed in the south, and salinity has risen to levels not far below saturation for some dissolved salts. Little effort has been made to mitigate these impacts; the diverted water is far too important economically. The chemical factory at the southern end of the lake is now served by a series of evaporation ponds into which water from the northern basin is pumped. Proposals to top up the lake with water from the Mediterranean Sea were seriously considered some years ago and an environmental impact assessment was made. The proposal has not been implemented so far.

As for the future, it is clear that diversions will continue and that water-levels will fall further. Early in the next millenium, the Dead Sea will be no more than a large reservoir of hypersaline or saturated brine functioning mainly as a 'mine' for the chemical industry.

Many accounts exist which feature the Dead Sea, from those largely concerned with historical and cultural features to those concerned with scientific matters. An introduction to the literature may be gained from Nissenbaum (1979, 1993). Other accounts of interest to scientists are those of Neev and Emery (1967). Excellent modern accounts of the limited biology of the lake are given by Oren (1992) and Oren and Gurevich (1995). The most recent comprehensive account is by Niemi et al., (1997).

6.5 LAKE CORANGAMITE

Lake Corangamite is the largest permanent lake on the Australian mainland (Fig. 6.10). Of volcanic origin, it is situated on the basaltic plains of western Victoria. Like all saline lakes, its morphometry varies with time; that for 1979, a year when water-levels were neither high nor low, is shown in Table 6.7. Recent fluctuations in water-level are shown in Fig. 6.11. Historically, levels have been lower and as high as those shown in the figure. In 1933, the level was about 1 m lower than the lowest value (at 113.4 m asl) and it is estimated that levels in 1875 were as high as those in 1956.

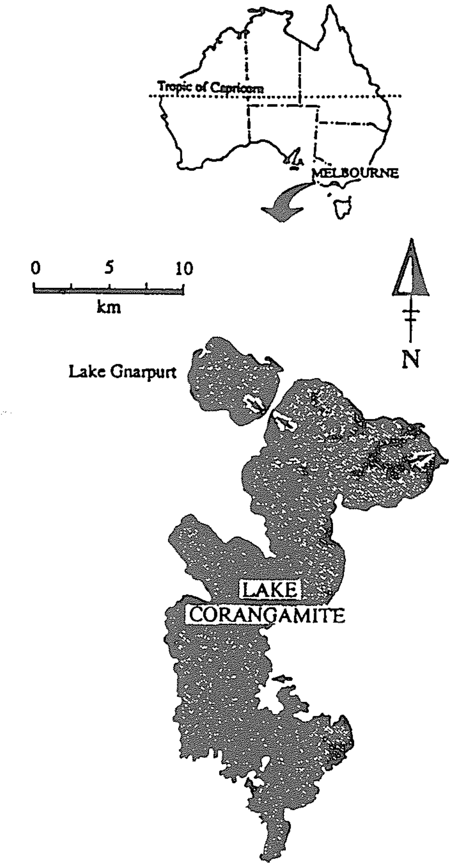

Fig. 6.10 Position of Lake Corangamite. After Williams (1995).

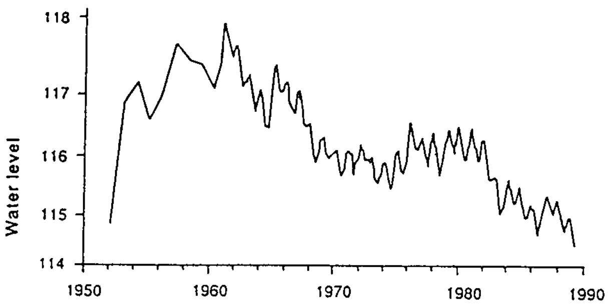

Fig. 6.11 Water-levels in Lake Corangamite between 1952 and 1990. Water-levels as m above sea-level.

Table 6.7 Major morphometric features of Lake Corangamite. Data from Williams (1995) after various authors.

Surface area (km^2)	251.6
Volume (km^3)	1.5
Maximum length (km)	30
Maximum width (km)	11
Maximum depth (m)	6
Mean depth (m)	6
Shoreline length (km)	159

Salinity is reasonably closely correlated with water-level (Fig. 6.12). The range is 18.4 g/L (1875) to 123 g/L (1939). Recent salinities (post 1950), for which data are firmer, have been between 20 and 60 g/L. Ionic composition (Table 6.8) indicates dominance by Na and Cl, with little variation in ion proportions with changing salinity.

Biodiversity is low but three broad faunal groups have been distinguished: one which occurs at both high and low salinities (e.g. *Calamoecia clitellata*, a calanoid, and *Haloniscus searlei*, an isopod), one found only at moderately low salinities, i.e. <~50 g/L (e.g. *Austrochiltonia*, an amphipod, *Coxiella*, a gastropod, and *Galaxias maculatus*, a fish), and one found only at high salinities, i.e. >50 g/L (e.g. *Australocypris robusta*, an ostracod). Some 20 bird species have been recorded, some in large numbers. Of plants, *Nodularia spumigena* is prominent in the phytoplankton, and the algae *Enteromorpha* and *Cladophora* and the macrophytes *Ruppia* and *Lepilaena* occur in the littoral when salinities are moderate.

Formerly, the lake was used for the 'extensive' aquaculture of eels which were largely exported; glass eels were caught in nearby estuaries, transported to the lake, and captured at maturity. However, at present the lake is of little or no economic value. Nevertheless, non-economic values attributed to the lake are high. It is regarded as of particular conservation value and, with others in the area, is recognized by the Australian government as a Ramsar site and in the Japan/Australia Migratory Bird Agreement (JAMBA) and China/Australia Migratory Bird Agreement (CAMBA). Within the state of Victoria, it has been recognized as a 'high value wetland' because of its ecological, scientific, educational, cultural and scenic values (see Williams, 1995).

All values of the lake are threatened by two impacts: the diversion of inflows and the addition of phosphate. The diversion involves the damming of the northern and most important inflow, the Woady Yaloak Creek, so that its waters enter the Barwon River which flows away from the lake. The dam was constructed after political pressure from local farmers following the flooding of marginal land in 1956. Thus, unlike other diversions discussed in this chapter, this diversion had nothing to do with the supply of economically useful water; it was merely to prevent flooding. The addition of phosphate is of more recent origin (post 1995). It involves the leaching of fertilizers applied to southern parts of the catchment to promote pasture growth for the benefit of the local dairy industry.

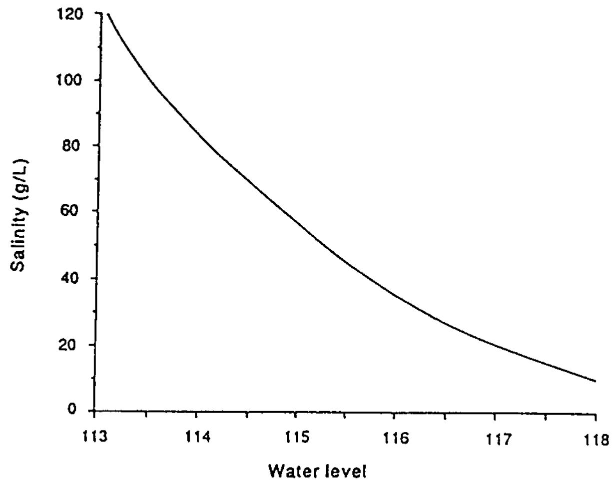

Fig. 6.12 Relationship between salinity and water-level (as m asl) in Lake Corangamite.

Table 6.8 Major ion composition of Lake Corangamite in March 1979. Data as g/L. From Williams (1995).

Ion	
Na	11.1
K	0.1
Ca	0.1
Mg	1.0
Cl	18.8
SO_4	0.6
HCO_3 + CO_3	0.85
Salinity	35.5

The effects of the impacts have been significant, especially the diversion. After 1956, water-levels inexorably fell and salinities rose, despite short-term changes to the contrary. By 1992, the levels had fallen so far that islands in the south of the lake used for breeding by birds became peninsulas, thus allowing access to the colonies by predators and their destruction. Birds also deserted the lake because their food - snails (*Coxiella*), shrimp (*Austrochiltonia*), fish (*Galaxias*) and macrophytes (*Ruppia*) - had largely disappeared as a result of the high salinity. The addition of phosphates led to the development of massive phytoplankton blooms. Thus, overall, the diversion and addition of phosphate has led to a significant deterioration in most of the more important values of the lake. Additional adverse effects include the development of medical problems (particularly asthma) in some people living near the lake. Some respite from the effects of diversion occurred after 1995 when increased rainfall raised the level of the lake and decreased salinity to below 50 g/L (with the return of the shrimp, snails, fish, *Ruppia* and other biota). No respite is in sight with regard to the addition of phosphate.

Conservation groups have long campaigned for the removal of the dam on the Woady Yaloak Creek. Their efforts have had some (limited) success since the maintenance of the dam is costly. In any event, stopping diversion is the most obvious management measure for lake restoration. Unfortunately, less success is likely with efforts to curb the entry of phosphate. Local farming communities (worldwide) are more concerned with immediate economic issues than those of national or international significance. Consequently, the prognosis for the lake is not a favourable one. If the natural water budget is restored, this will certainly lead to a restoration of natural water-levels and salinities. However, these events are likely to be overridden by the adverse effects of continued addition of phosphates. On this matter, attention is again drawn to the fact that water quality criteria designed to protect freshwater, open hydrological systems (in this case, criteria for phosphate loads) are mostly inapplicable for the protection of saline, closed systems. The most likely prognosis for Lake Corangamite on present evidence is that it will become a highly eutrophic lake, with more or less continuous algal blooms, little if any bird life, and of limited conservation value.

The most recent information on the lake is given by Williams (1995) who summarizes previous published and unpublished work.

6.6 MONO LAKE

Mono Lake is located within a tectonic basin east of the Sierra mountains in California at an altitude of just under 2,000 m asl. Volcanic activity during the past 33,000 years has modified the form of the lake, but its modern shape and bathymetry are shown in Figs 6.13 and 6.14. Morphometric features at high and lowest water-levels in the past 90 years are given in Table 6.9. The great difference between values reflects the effects of diversion which began in 1941.

Salinities have moved more or less in tandem with the changing water-level and values range from 52 g/L, when water-level was highest, to 95 g/L in 1982 at the lowest water-level. Some variation in ionic composition has occurred with changing salinities - particularly in anion proportions - but it is not great, and at all salinities Na dominates the cations (>95%), and HCO_3 + CO_3 and Cl are the most important anions but with significant amounts of SO_4 (~16%; Table 6.10).

Biodiversity is low though biological production is high. Major elements of the aquatic fauna are the endemic brine shrimp (*Artemia monica*) and the brine-fly (*Ephydra hians*). There are no fish. However, the abundant populations of the brine shrimp and fly support a relatively diverse bird fauna including many migrants. Notable migrants are Wilson's phalarope and the eared grebe. Species with resident breeding populations include the California gull.

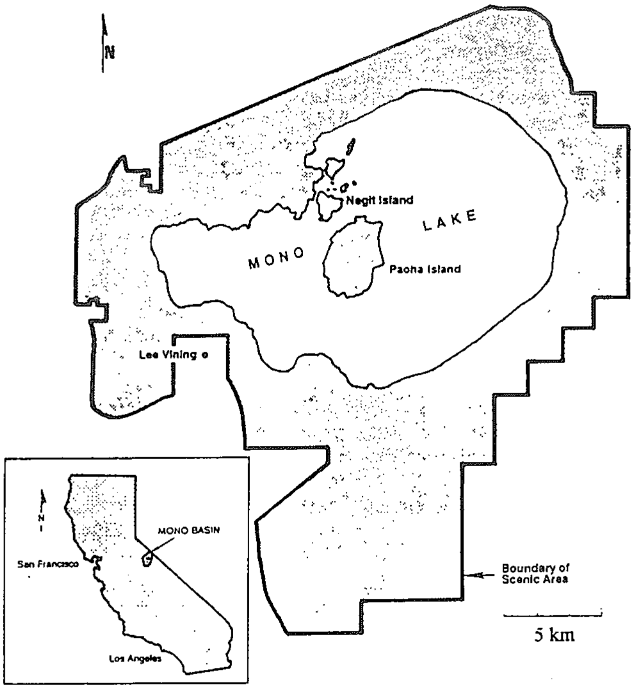

Fig. 6.13 Outline and position of Mono Lake. After various authors.

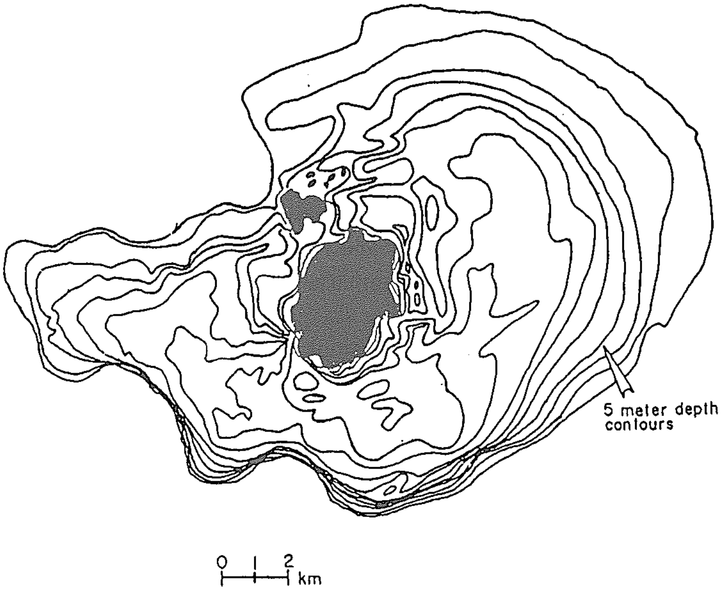

Fig. 6.14 Bathymetry of Mono Lake. After various authors.

Table 6.9 Major morphometric features of Mono Lake near highest water-levels and at lowest level. Data after various sources.

	Water-level (m asl)	
	1,954	1,942
Surface area (km^2)	223	158
Volume (km^3)	5.0	2.8
Maximum length (km)	~20	<20
Maximum width (km)	~7	<7
Maximum depth (m)	56.7	45.7
Mean depth (m)	22.9	15.2
Shoreline length (km)	96.5	56.3

Table 6.10 Major ionic composition of Mono Lake (1977). Data as g/L and after Hammer (1986).

Ion	
Na	29.5
K	1.5
Ca	<0.0
Mg	<0.0
Cl	17.6
SO_4	10.3
HCO_3 + CO_3	30.1
Salinity	89.0

Many values have been attributed to the lake. The lake was of cultural importance to the Paiute Indians for whom its shrimp provided food. The past and present aesthetic appeal of the lake and its surrounding landscape has attracted and continues to attract many sightseers. Visitors not only engage in passive recreation but also boat, swim, birdwatch and walk. Because of the high salinity, low biodiversity, and the interaction between these, the lake continues to attract attention from scientists and educators. As noted, the lake is a feeding and breeding site for birds, and is particularly important as a stopover feeding site for migrating Wilson's phalarope, the eared grebe and other shorebirds. Economically, the lake is important because of its production of brine shrimp (of minor value) and because its inflows are fresh.

Diversion of inflows is the only significant impact and threat to the lake. Beginning in 1941, the Los Angeles water authorities began to divert water down the Owens Valley for domestic supplies. As a consequence, the level of the lake began to fall steadily - from 1,956 to 1,942 m asl (1982), a drop of 14 m (Fig. 6.15). The effects of this have been an almost two-fold increase in salinity, the exposure of considerable areas of the lake bed (including calcareous tufa), and the conversion of islands to peninsulas so allowing access for the coyotes to predate colonies of California gulls. The exposure of the lake bed also gave rise to alkali dust storms in windy conditions. The ecological effects of the salinity increase have not been fully documented but studies indicate that growth and reproductive rates for many species have been reduced (e.g. Herbst, 1988; Herbst et al., 1988).

The effects of the water diversion have sparked considerable community debate. In response to this and public concern, the California Department of Water Resources convened an "Interagency Mono Lake Task Force" in 1978. This was charged with the development of a plan of action to preserve the lake. It recommended that diversions be curtailed and the level raised. In 1982, a resolution urging conservation of the lake was forwarded to the US President (Reagan) by the scientific community. Further public and other concern led to the formation of the Mono Basin Ecosystem Study Committee (Patten et al., 1987) following a Congressional directive. After the passage of the California Wilderness Act in 1984, the Mono Basin National Forest Scenic area was established under the management of a federal agency. Finally, in 1994, the State of California decided to amend the water rights of Los Angeles. The decision limited diversions until water-levels reached 1,984 m asl and was a clear and enlightened management response to the ongoing environmental degradation of the lake. As such, it represents the first restorative management action undertaken for any saline lake impacted by diversion of inflows. Thus, the prognosis for Mono Lake is favourable; it is likely that all of its values will be maintained, and those degraded by the diversions will be restored to a significant extent.

Mason's (1967) study of the lake was a milestone. The most recent comprehensive general account is that by Patten et al., (1987). Other recent, less comprehensive, accounts include those of Dana et al., (1993), Jellison and Melack (1993), and Stine (1990).

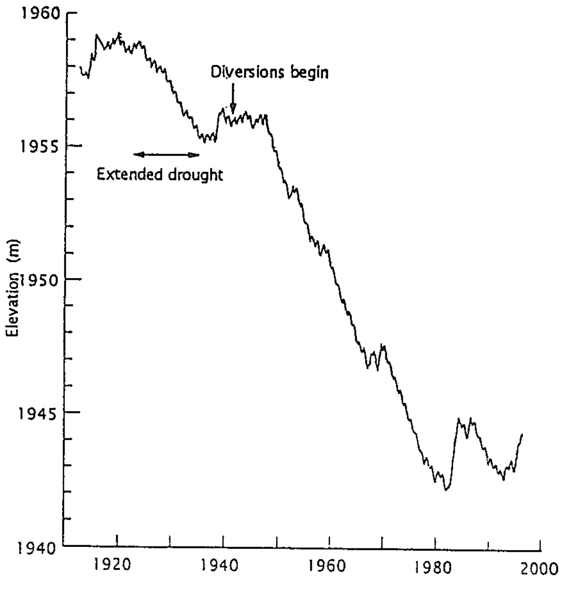

Fig. 6.15 Water-levels in Mono Lake. After various authors.

6.7 MAR CHIQUITA

The Laguna de Mar Chiquita (here, simply Mar Chiquita) is a large tectonic lake located in northern Argentina at about 70 m asl. Despite little reference to it in the limnological literature, it is one of the world's largest lakes (with a surface area in 1982 of almost 6,000 km^2) and is certainly the largest lake in Argentina (Fig. 6.16). Its major morphometric features are given in Table 6.11 for 1977 and 1982, periods of low and high water-levels. Comparing the data for these two years emphasizes the variability of the system: in area alone, the lake increased threefold in only five years. Geomorphological evidence points to a long history of hydrological instability - successive periods of flooding and drying. Local anecdotal evidence indicates that the lake was completely dry less than a century ago (in 1910). The recent rises in water-level, note, are contrary to the general worldwide trend of falling levels in large, permanent salt lakes (Williams, 1993).

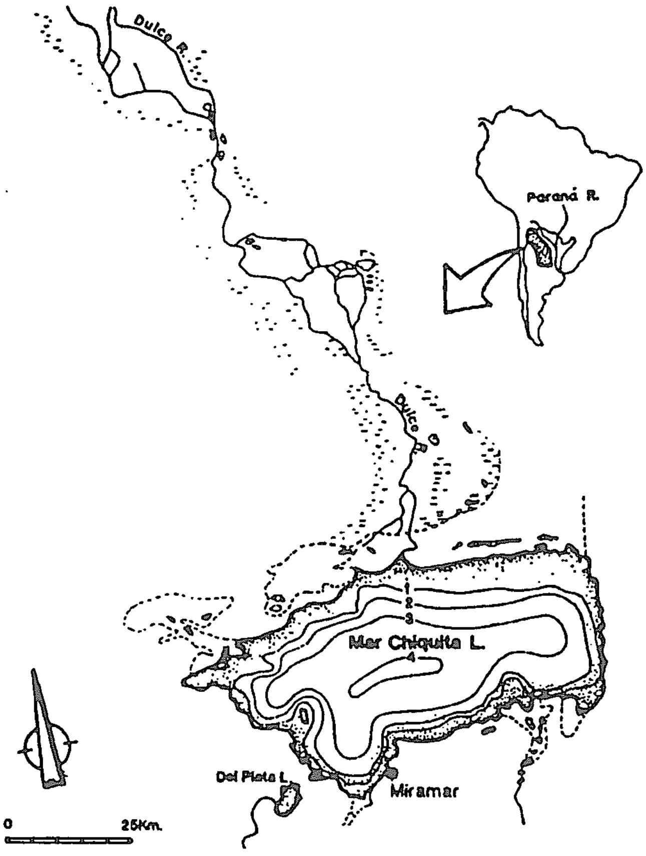

Fig. 6.16 Position and bathymetry of Mar Chiquita. After Reati et al., (1997).

Table 6.11 Major morphometric features of Mar Chiquita during a period of low water-levels (1977) and high water-levels (1982). Data from Reati et al., (1996).

	1977	1982
Surface area (km^2)	1,960	5,770
Volume (km^3)	4,240	21,400
Maximum length (km)	76	140
Maximum width (km)	40	100
Maximum depth (m)	4.1	8.6
Mean depth (m)	2.15	3.7
Shoreline length (km)	240	440

Table 6.12 Major ionic composition of Mar Chiquita during a period of low water-level (1970) and high water-level (1982). All data as g/L and from Martinez (1995).

Ion	1970	1982
Na	107.3	10.7
K	1.6	0.2
Ca	1.0	0.3
Mg	0.7	0.1
Cl	143.7	13.6
SO_4	27.9	4.5
$HCO_3 + CO_3$	0.1	0.5
Salinity	282.3	29.9

Salinity is generally inversely related to water-levels and throughout the present century has varied between 25 (1982) and 360 g/L (1911-12). Data on major ion composition are given in Table 6.12 which gives data for 1970, a year of high salinity and low water-level, and 1982, a year of low salinity and high water-level. Two salient points emerge. First, the lake is dominated, as are most salt lakes, by Na and Cl; and second, little variation in ionic proportions occurs over the range of salinity.

The biota has varied in accord with salinity. Under hypersaline conditions, it appears that *Artemia* dominates the aquatic fauna, with the Chilean flamingo, *Phoenicopterus chilensis*, a dominant member of the bird fauna maintaining large breeding populations. In less saline conditions, a wider diversity of invertebrates occurs together with fish, but the flamingos no longer breed. Some 60 species of birds have been recorded during low salinity phases.

The lake has several values, which change in extent according to the condition of the lake. Thus, when hypersaline, therapeutic values are highly regarded and encourage tourism as does the large population of flamingos. When the lake is only moderately saline, on the other hand, its alleged therapeutic values decline, and the flamingo no longer breeds. At the same time, it is invaded by fish and these form the basis of a small commercial fishery. The major species involved is the Argentine silverside, *Basilichthys bonariensis*. Commercial breeding and trapping of the amphibious coypu, *Myocastor coypus*, should also be mentioned. A diverse and abundant bird fauna is found at moderate to low salinities too. This avifauna, together with the use of the lake as stopover feeding site by migrant species, led to the inclusion of the lake in the Western Hemisphere Shorebird Reserve Network.

At present, under high water-levels and low salinities, the main environmental impact is the illegal poaching of birds. However, greater threats loom: land reclamation, stream and wetland drainage, and inflow diversion. The latter is likely to be the most important as it involves the Federal Canal Project, a proposal to divert a large proportion of the water from the Dulce River for irrigation and water supply. The likely impact of this will be a significantly reduced lake, of higher salinity, and with degraded conservation values. If large quantities of water are diverted, the lake will disappear altogether, as it has in the past, but now permanently. The prognosis is a bleak one. Several Argentinean scientists have already pointed to the irreversible loss that this would be to a series of economic, environmental, cultural, scientific and ecological values.

Knowledge of the lake is not comprehensive. However, two recent papers add significantly to it as well as listing previous work (Martinez, 1995; Reati et al., 1996).

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