Salinization: unplumbed salt in a parched landscape

W.D. Williams,
Emeritus Professor, International Lake Environment Committee Foundation (ILEC), Australia

Abstract The global hydrological and salt cycles are described, as are the ways in which human activities have led to their disturbance. One effect of this disturbance is the unnatural increase in the salinity of many inland waters (secondary salinization). The geographical extent of secondary salinization is outlined, together with its effects on various types of inland waters, such as salt lakes, freshwater lakes and wetlands, and rivers and streams. The likely impact on salinization of global climate change is summarized.

Keywords Salt; secondary salinization; global cycles; inland waters

Introduction
The title of this lecture was evoked by a line in a poem by Matthew Arnold (1822–88) who referred to unplumbed salt, with “unplumbed” meaning deep. I use the word unplumbed in its alternative sense, meaning not part of the planet’s natural “plumbing” system, that is, not part of global hydrological and salt cycles. I hope this allusion will become clear later.

In this lecture, I discuss the broad nature of these cycles, and indicate how human activities have led to their disturbance. One effect of disturbance has been unnatural increases in the salinity (sum concentration of total dissolved salts) of many inland waters (secondary salinization). I outline the geographical extent of secondary salinization and the effects on various sorts of inland waters, notably salt lakes, freshwater lakes and wetlands, and rivers and streams. Finally, I summarize the likely effects of global climate change on salinization.

The aim of the lecture is to highlight salinization as a major global environmental phenomenon which has already significantly degraded many water resources and which will undoubtedly continue to do so at an accelerating rate. Attention was drawn to the hazard of salinization to streams and rivers over a decade ago (Williams 1987) and many regional concerns and site specific examples have been noted since. Even so, salinization as a major global geochemical event seems largely to lie outside the consciousness of most water resource managers, conservationists and limnologists if not all (see, for example, Naiman et al. 1995). Evidence is provided by the lack of attention it receives at international water resource conferences and in textbooks. For example, it scarcely rated mention at the recent Eighth International Conference on the Conservation and Management of Lakes sponsored by ILEC in Copenhagen in 1999 (apart from my own paper: Williams 1999a), nor the Second World Water Forum in The Hague earlier this year. Likewise, no mention is made of it in two recent and influential limnology texts, those by Lampert and Sommer (1997) and Moss (1998). Salinization is not even listed in the otherwise extensive table of major water quality issues in the global assessment of freshwater diversity by Groombridge and Jenkins (1998).

The reasons behind the lack of attention are undoubtedly because salinization is not a major issue in northern temperate regions. I hope this lecture will alert and inform those with interests and concerns beyond these regions, particularly in that half of the total land area where mean annual rainfall is less than 750 mm (drylands).
Global hydrological and salt cycles

The global hydrological cycle involves three core processes: evaporation, precipitation and temporary retention of water on the world’s continents. The interrelationships between these underpin the origin and fundamental chemistry of all inland waters. Three facts stand out: (i) more water evaporates from the ocean than is directly returned in precipitation over it; (ii) more water is precipitated over land than evaporates from it; and (iii) the surplus of precipitation over evaporation on land ultimately returns to the ocean after retention in lakes and other water-bodies.

No elaboration of this elementary outline is needed here. Of some interest, however, are estimates of the volumes of water involved. A range exists. A recent estimate is that $505 \times 10^3 \text{km}^3$ of water evaporates from the ocean annually. Ninety per cent of it is directly returned in rainfall. The remainder, $50.5 \times 10^3 \text{km}^3$, precipitates over land. Here, together with precipitation of local origin, total annual precipitation is $119 \times 10^3 \text{km}^3$ of which $72 \times 10^3 \text{km}^3$ evaporates. The difference, $47 \times 10^3 \text{km}^3$, represents run-off to the ocean. Thus, approximately the same volume of water is cycled annually between the ocean and land areas.

Although oceanic evaporation produces water essentially free of electrolytes, all precipitation contains small but significant amounts of dissolved salts. The mostly oceanic origin of these salts in precipitation over land areas is demonstrated by the distribution of isoclines of rainfall salinity: coastal rain has a higher salinity than inland rain. Thus, allied to the hydrological cycle are cycles of oceanic salts (often referred to as “cyclic salts”).

For the most part, cycles of major inorganic salts are ignored in the limnological literature, and no recent estimates of actual amounts cycled are readily available. Nevertheless, the long-term chemical stability of the ocean suggests that on a geological time-scale a balance exists between (1) the mass of salt transferred from the ocean to the land in precipitation and marine deposits, and (2) the mass of salt returned to the sea from the land and derived from salt in precipitation and from weathering of old marine and other deposits. However, this long-term balance is contradicted if the salinities of total run-off and precipitation are considered: there is a significant imbalance between (1) and (2). As indicated, the mass of water transferred in precipitation from the ocean to land annually is $50.5 \times 10^3 \text{km}^3$. Its salinity is highly variable but a figure of $10 \text{mg L}^{-1}$ has been advanced as an approximate one. Thus, the total mass of salt transferred from the ocean to the land in precipitation annually is $\sim 50.5 \times 10^{10} \text{kg}$. The total mass of salt transferred from the land to the ocean annually in run-off, on the other hand, is almost a magnitude greater, $\sim 564 \times 10^{10} \text{kg}$ (derived using a total annual run-off of $47 \times 10^3 \text{km}^3$ and a world average river salinity of $120 \text{mg L}^{-1}$). This additional salt must be derived from the weathering of salt deposits of ancient marine origin or terrestrial sources. Whatever the case, note that the additional salt load still represents just $10^{-7}$ of the total oceanic salt mass (given a total oceanic volume of $1.34 \times 10^9 \text{km}^3$ and a mean salinity of $35 \text{g L}^{-1}$).

These calculations show that global hydrological and salt cycles involve:
- a large annual flux in water volumes and salt mass
- the movement of large volumes of slightly saline water across land-masses
- the transference to the ocean from land of significant amounts of salt not of immediate “cyclic” origin, suggesting large stores of inland salt.

In short, large amounts of salt move through, and occur in, the terrestrial environment.

Salinization and its causes

Regional climatic and topographic differences add complexity to the global hydrological and salt cycles outlined above, so that in endorheic (closed) drainage basins salt is retained and accumulated for long periods, whereas in exorheic (open) drainage basins salt is rapid-
ly returned to the sea. The natural retention and accumulation of salt in endorheic regions results in the development of salt lakes, and this process is primary or natural salinization. Natural salinization has caused almost 45 per cent of global epicontinental waters to become more saline than 3 g L\(^{-1}\) (i.e. saline).

Like many other geochemical cycles, the salt cycle has been significantly disturbed by human activities. The disturbance is manifested largely as increased salinities in lakes already naturally saline, by increases in the number of salt lakes, and by increased salinities in freshwater lakes and wetlands and rivers and streams. This process is secondary salinization or, often, simply salinization.

For salt lakes to develop, i.e. for natural salinization to occur, two basic conditions must be met. The lake must be the terminus of an endorheic drainage basin and a balance must exist between inflows (influents and precipitation) and outflows (evaporation and seepage). Assuming no loss of solutes to sediments, lake salinity in relation to the balance between evaporation and precipitation is given by: 

\[ f_1 = \frac{(v)_{\text{ev}} - (v)_{\text{prec}}}{(v)_{\text{inf}}} \]

where \((v)_{\text{ev}}\) is mean evaporative loss, \((v)_{\text{prec}}\) is mean precipitation, and \((v)_{\text{inf}}\) is mean inflow volume. For different values of \(f_1\), the relationship is shown graphically in Figure 1.

The figure indicates that salt lakes can form only where net evaporation is greater than net precipitation. Note that the relationship is hyperbolic, but it is of some interest to record that the median salinity of salt lakes in regions where they are common is markedly less than saturation values. This indicates significant loss of salt by deflation and/or seepage to sediments. Salt lakes are far from “closed” basins. It may also be noted that the total volume of inland saline lakes \((85 \times 10^6 \text{km}^3)\) is not much less than that of freshwater lakes \((105 \times 10^6 \text{km}^3)\).

Secondary salinization has quite different origins. There are several. In brief, they are:

- clearance of natural deep-rooted vegetation from catchments and its replacement by pasture and other agricultural crops
- drainage of agricultural saline waste water from irrigated regions
- rising saline groundwaters and saline intrusions
- diversion of inflows from salt and freshwater lakes for irrigation
- construction of impoundments on rivers
- construction of salt storage basins
- brine discharges from mining activities.

For the most part, these events essentially involve the mobilisation and redistribution of inland salt (of both surface and subsurface origin), that is, changes to the natural patterns of

\[ \text{Figure 1} \] The relationship between lake salinity and inflow salinity and the balance between evaporation and precipitation. After Carmouze and Pedro (1977)
salt distribution and movement. Global hydrological and salt cycles, the planet’s “plumbing” system, have been disturbed; alterations have been made to the natural patterns of storage and dispersal of salt.

**The geographical extent of secondary salinization**

Natural and secondary salinization are confined to, or most commonly found in, semi-arid and arid regions, i.e. where the mean annual rainfall is between 25 and 500 mm. They also occur in sub-humid regions, i.e. where the mean annual rainfall is between 500 and 750 mm. The total land area of the world receiving less than 750 mm of annual rainfall (so-called drylands) is often underestimated. It is extensive and not much less than 50 per cent of total land area. If sub-humid regions are excluded, drylands cover 33 per cent of total land area, with 25 per cent representing semi-arid and arid regions. That is, salinization is an actual or potential environmental threat for a quarter of the world’s total land area and water-bodies within that area. However, semi-arid and arid regions are not evenly distributed between continents. Most of Europe and eastern North America is not semi-arid or arid; most of Australia and the Middle East is. Table 1 illustrates this point for continents where >10 per cent of land area is semi-arid or arid.

**Table 1** Areas of semi-arid and arid lands in various continents.

<table>
<thead>
<tr>
<th>Continent</th>
<th>Area × 10^6 km^2</th>
<th>Per cent continental area</th>
</tr>
</thead>
<tbody>
<tr>
<td>North America</td>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td>South America</td>
<td>3</td>
<td>17</td>
</tr>
<tr>
<td>Africa</td>
<td>18</td>
<td>64</td>
</tr>
<tr>
<td>Asia</td>
<td>16.5</td>
<td>39</td>
</tr>
<tr>
<td>Australia</td>
<td>6.4</td>
<td>83</td>
</tr>
</tbody>
</table>

An important point to make in this connection is that salinization is therefore important in many parts of the semi-arid world where human populations are most rapidly growing: central and South America, south-western North America, the Middle East, and central Asia. Already some 400 million people inhabit these regions. It is water-bodies and water supplies in their habitats that have been most degraded and will further degrade.

The degree to which secondary salinization has already degraded inland waters is difficult to determine, but an estimate of $9.5 \times 10^6$ km$^2$ has been advanced for the global area of land that has been damaged, with over 10 per cent of all irrigated land already damaged. Whatever the estimates, it is certainly true that the salinity of many large rivers in drylands has risen. In some countries, secondary salinization is now regarded as the most significant threat to the viability of rivers (Davies and Day 1998).

**The effects of secondary salinization on aquatic environments**

The overall biological effects of secondary salinization on aquatic environments are:
- changes to the natural character (processes and structure) of water-bodies
- loss of biodiversity
- taxonomic replacement (less halotolerant species are replaced by more halotolerant species).

All of these effects are undesirable and largely irreversible: they cause more or less permanent degradation. The loss of biodiversity is probably greater than generally realized since recent work on both fresh and saline waters in semi-arid and arid regions indicates they have much greater biodiversity than was thought (e.g. Williams 1999b). Other effects are equally adverse. Salinization leads to significant decreases in water quality for irriga-
tion and other uses, the loss of amenity and aesthetic values, extensive habitat loss, and reduced environmental attributes (e.g. conservation values). The economic costs alone are immense. The nature of the biological effects differs according to the nature of the habitat affected. Three major sorts of habitat can be considered here: salt lakes, freshwater lakes and wetlands, and rivers and streams.

**Salt lakes**

Many large and permanent salt lakes have been affected by secondary salinization. For the most part, salinities have risen. In almost all cases, the rises followed diversions from inflowing rivers: with decreased inflows, lake volumes decreased and so solutes became more concentrated.

The extent of the increase in salinity and its effects differ between lakes according to the volumes of water diverted from inflowing rivers, the initial salinity of the lake, and lake morphometry. In the Aral Sea, the increased salinity and fall in water-level (15 m between 1960 and 1991) led to a large decrease in the surface area of the lake, the exposure of extensive areas of the former lake bed, and the demise of the south-eastern archipelago. Consequently, shipping became impossible, the frequency of dust storms around the lake increased, summers became hotter, the incidence of respiratory and other human diseases increased in the local human population, and nearby agricultural productivity fell (because of the additional salt load from the bed of the lake). The damage to the lake itself was also extensive. The biota of the lake changed radically, the loss of the southern archipelago caused the disappearance of extensive areas of wildlife and bird habitat, and the commercial fishery collapsed. As well, much of the aesthetic and cultural value of the lake was lost. Not all of these impacts have resulted from the secondary salinization of other large salt lakes, but falling water levels, increased salinities and changes to natural ecological conditions have almost always occurred. Globally, therefore, the salinization of many large salt lakes has caused significant environmental, economic and social losses.

If continued, water diversions from salt lakes lead to the complete desiccation of the lake. Several examples are already known, though not well documented. Owens Lake in California is a case in point. Before its inflowing rivers were diverted, this lake was about 24 km long, 16 km wide and 10 m deep. Salinities between 1890 and 1914 were from 16 to 214 g L\(^{-1}\). After 1913, diversion of inflows had led to the complete desiccation of the lake by 1924. Apart from noting the complete loss of the lake, one other impact is notable: the desiccated lake bed produces marked emissions of small dust particles to the atmosphere and the bed itself has high levels of phytotoxins such as arsenic and boron. Irrigated planting is now attempting to control dust emissions.

**Freshwater lakes and wetlands**

Many freshwater lakes and wetlands occur in semi-arid if not arid regions and may undergo secondary salinization following extensive changes to land-use in their catchments. Irrigation and clearance of the natural vegetation are the most important events in this regard. Both events commonly mobilize subsurface salt and the mobilized salt salinizes freshwater lakes and wetlands within the catchment. Rising saline groundwaters may threaten floodplain wetlands in certain regions.

There are many examples in Australia. In south-western Australia, most formerly freshwater lakes are now saline. On the floodplain of the River Murray in south-eastern Australia, many wetlands also face salinization. In this area, management practices often involve lowering the groundwater table by pumping, with much of the pumped and slightly saline water stored at the surface in so-called “evaporation” or “recharge” basins. These basins are located not far from the River Murray; there are already 200 on the floodplain.
Evaporation basins are at best a short-term management solution and may give rise to additional problems. Those in California, for example, may accumulate selenium, a toxic element which has affected local waterfowl populations adversely.

Fewer examples of freshwater lakes and wetlands that have been secondarily salinized are known outside Australia. However, Lake Qarun, south-west of Cairo, Egypt, and formerly fresh, has become saline because of salt inflows in drainage water from nearby agricultural land. Increases in the salinity of some freshwater lakes in the Rift Valley of Ethiopia have been attributed to irrigation, river diversions and deforestation. A few examples are also known from temperate regions. Some of the artificial lakes created by open-cast coal-mining in Germany are now being salinized by saline groundwater and salt mines have salinized several freshwater lakes in Cheshire, UK. Reservoirs too can be threatened by secondary salinization. For example, waters impounded by the Imperial Dam on the lower reaches of the River Colorado, USA, will soon have salinities >1.1 g L\(^{-1}\). Salinity is a major environmental factor for this river and its many impoundments.

Even small salinity rises can be significant for freshwater lakes and wetlands since their biota generally has a limited halotolerance. The disappearance of macrophytes and riparian trees is one of the first signs that secondary salinization is in process. Apart from ecological damage (changes in natural character, biodiversity loss, taxonomic replacement), secondary salinisation involves many other disbenefits. Economic losses include the loss or reduced value of the lake or wetland for water supplies. Decreases in conservation, amenity, aesthetic, and general environmental values also occur. For floodplain wetlands, losses include degradation of the riverine system as a whole because of the close hydrological and ecological relationship between floodplain wetlands and rivers (e.g. Davies et al. 1994).

**Rivers and streams**

The secondary salinisation of rivers and streams is closely related to that of freshwater lakes and wetlands. This is because rivers and streams either arise in salinized catchments and discharge salt into lakes and wetlands or flow from them with additional salt loads. Both small streams and large rivers may be subject to secondary salinization. The Blackwood River, south-western Australia, provides a well documented example of a river that has been salinized during the past 200 years by catchment changes; its catchment has been extensively cleared for agricultural purposes. Less than a century ago, its salinity was <0.5 g L\(^{-1}\) throughout the river; it is now mostly >3 g L\(^{-1}\). Other examples include the Colorado River, south-western USA, and the Syr and Amu darya, central Asia, which discharge into the Aral Sea. The salinity of the lower reaches of the Syr darya has increased seven times in the past 90 years.

Ecological effects are largely similar to those for freshwater lakes and wetlands. However, it is often difficult to separate ecological effects due to secondary salinization from those resulting from the other two major anthropogenic disturbances to rivers and streams in drylands, flow regulation and diversion. Economic effects are more easily distinguished; when salinities reach 1 g L\(^{-1}\), the water is generally useless for agriculture, domestic consumption and many industrial uses. Thus, the economic costs may be very large. Managers become alarmed when even small rises occur, as they are, for example, with regard to the River Murray, south-eastern Australia, a major source of irrigation water and supplies for the city of Adelaide. Economically important rises in salinity, however, may not be as important for environmental values because the biota may have evolved a tolerance to the small and natural salinity fluctuations characteristic of many flowing waters in dryland regions. Even so, recent investigations indicate that the extent of this natural halotolerance may be limited, so that the ecological effects of small salinity rises in rivers and streams should not be underestimated.
Likely effects of global climate change on secondary salinization

Climate has changed within historical times and many climatologists predict even greater changes within the foreseeable future. The Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 1996) predicts an average increase in global temperature of 2°C in the present century with effects becoming obvious within the next few decades. Although most attention is paid to increased global temperatures, climate change is likely to result more from changes in the hydrological cycle: precipitation, evaporation, evapotranspiration, run-off and cloud cover. Aquatic habitats in drylands are particularly vulnerable to change since they are already sensitive to a range of climatic factors (see, for example, Figure 1). Indeed, this sensitivity is the reason why palaeolimnological studies of salt lakes are of such interest to palaeoclimatologists. The sensitivity of other water-bodies in drylands to climate change has also not escaped notice (e.g. streams).

Available models predicting the nature of climate change indicate a variety of scenarios for drylands. Overall, however, it seems that they will become hotter and many will become drier (Ragab et al. 2000). The implications for secondary salinization are obvious: it is likely that further human activities will occur designed to counteract the increased aridity (e.g. more irrigation, more river diversions, more impoundments) and so exacerbate the causes of secondary salinization. Exactly how the linkage between the changed hydrological cycle and the salt cycle will be affected is still uncertain. What is not uncertain, however, is that secondary salinization, already an important phenomenon in drylands, will become even more important in an increasingly parched landscape.

References


