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Salinisation: A major threat to water resources in the arid and semi-arid regions of the world

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Abstract

Semi-arid and arid regions (i.e. drylands with annual mean rainfall between 25 and 500 mm) cover approximately one-third of the world's land area and are inhabited by almost 400 million people. Because they are a resource in short supply, waters in drylands are under increasing human pressures, and many are threatened by rising salinities (salinisation) in particular. Rising salinities result from several causes. The salinities of many large natural salt lakes in drylands are rising as water is diverted from their inflows for irrigation and other uses. The excessive clearance of natural, deep-rooted vegetation from catchments and the discharge of saline agricultural wastewater causes the salinity of many freshwater lakes, wetlands and rivers to rise. The salinisation of some fresh waters is caused by rising saline groundwaters. And in some regions, increasing climatic aridity may be a cause of salinisation. Whatever the cause, salinisation has significant economic, social and environmental impacts. They are usually deleterious and often irreparable. Decreased biodiversity, changes in the natural character of aquatic ecosystems, and lower productivity are frequent ecological effects. In some dryland countries, salinisation is viewed as the single most important threat to water resources. However, the extent and importance of salinisation as a global threat has been greatly underestimated. Recognition of this is the first step in any attempt to manage it effectively. The aims of the present paper, therefore, are three-fold. First, it aims to define the problem and indicate its extent; second, it aims to outline the causes and effects of salinisation; third, it aims to highlight the social, economic and environmental costs and comment on management responses. An overarching aim is to draw attention to the importance of salinisation as a phenomenon of global significance to waters in drylands.

Key words

arid, drylands, dryland salinity, salinisation, salt lakes, secondary salinisation, semi-arid, water resources.

INTRODUCTION

Salinisation is the process that increases the salinity of inland waters. Two types can be distinguished: one natural, and one anthropogenic, so-called 'secondary salinisation'. This paper focuses on secondary salinisation.

Natural (primary) salinisation is essentially restricted to closed (endorheic) drainage basins in semi-arid and arid regions of the world; these regions are also where secondary salinisation is most common. The area of semi-arid and arid regions (drylands) is almost one-third of total land area. In these regions, annual rainfall is 25–500 mm, and more than 400 million people live there. This number is increasing and so, therefore, are human demands and impacts upon water resources in drylands. Secondary salinisation is one of the most important of these impacts and its importance, too, is increasing. However, although the significance of salinisation as a threat and impact is well recognized at national levels, its global extent, ubiquity and importance is less recognized. For example, Groombridge and Jenkins (1998) note that salinisation is a water quality issue that is 'not globally important, but may be of local significance'. On the other hand, in some dryland countries, it is seen as the most important threat to the viability of water resources (e.g. in South Africa: Davies & Day 1998). Given expectations concerning the nature of global climatic change, it is likely that its importance will increase even further following future extension of dryland areas (Houghton *et al.* 1996).

The impacts of secondary salinisation are always adverse, manifold, and for practical purposes, irreversible. When large lakes that are already saline are involved, diversions of inflowing rivers are the main cause. The impact of rising salinities in these lakes depends upon both their original

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(natural) salinity and the extent of the increase in salinity. Greatest impacts occur when original salinities are low. Overall, most values of the lake (economic, environmental, for conservation, and ecological) degrade. Major causes of salinisation of fresh waters are catchment activities that alter hydrological balances and mobilize underground salt. The impact of salinisation, here, largely depends on the extent of the increase in salinity alone. However, freshwater ecosystems are considerably more sensitive to salinity increases than salt lakes, and even small rises have large effects.

The aims of this paper are three-fold. A first aim is to define salinisation and indicate its global extent. A second aim is to outline its causes and effects. And a third aim is to highlight the costs of salinisation and comment on prophylactic and remedial measures (management responses). An overarching aim is to draw the attention of water resource managers, limnologists and conservationists to salinisation as an important global impact on and threat to the viability and natural integrity of many, and perhaps most, waters in semi-arid and arid regions.

Both standing and flowing waters in drylands may be impacted upon or threatened by salinisation. The most important types involved (but not the only ones) are: (i) large, permanent salt lakes; (ii) small to large and usually permanent freshwater lakes and wetlands; and (iii) rivers and streams. Separate discussion of these types is an effective way to address the paper's aims.

SALINISATION AND ITS GLOBAL EXTENT

The occurrence of all inland surface waters is because more water evaporates from the world's oceans than precipitates over them. The difference, as rain or snow, falls over land and gives rise to all epicontinental and most hypocontinental waters. The rain or snow contains small amounts of salt derived from the ocean and this salt is deposited on to the land (in decreasing amounts away from the coast). In exorheically drained (open) basins, the salt is more or less directly returned to the ocean, but in endorheically drained (closed) basins, it accumulates in terminal basins where, following solar evaporation, it gives rise to saline lakes. This process is 'natural (primary) salinisation'. Note that the total global volume of water retained in saline lakes ($85\,km^3 \times 10^6$) is not a great deal less than that of total global surface fresh waters ($105\,km^3 \times 10^3$) (Shiklomanov 1990).

The accumulation of oceanically derived salt in salt lakes is not permanent and salt is lost by deflation, underground seepage and in other ways. This explains why the median salinity of salt lakes in regions where they occur is usually well below saturation values. Over geological time, therefore, a natural equilibrium has been established in inland surface waters, including saline ones, between salt inputs (salt derived from the ocean and other sources), salt retained for short or longer periods, and salt ultimately lost to the ocean. It is likely that human activities have not disturbed this equilibrium to any sensible extent. However, it is certain that they have disturbed the distribution of salt in inland waters: in particular, they have led to increased salinities in many of them, a phenomenon widely referred to as secondary salinisation when the process involves fresh waters. The term is equally applicable when the process involves increases in the salinity of waters already saline from natural causes. It is used in that sense here also.

Both natural and secondary salinisation are either restricted to or most common in semi-arid and arid regions of the world, almost one-third of total land area. Global climatic change is likely to increase this fraction, as indicated. Semi-arid and arid regions are not, however, equally distributed between continents; most of Europe and North America (but certainly not all) is not arid or semi-arid, whereas a good deal of Australia and Africa are. Secondary salinisation therefore is not an important impact upon waters where most of the world's population lives. It is important in parts of central and South America, large tracts of northern and southern Africa, the Middle East and central Asia, and many parts of Australia. The population of these regions, nevertheless, is not inconsiderable and is growing (400+ million). Paradoxically, it is noted that some of the world's largest lakes, reservoirs and rivers occur in these regions.

THE SALINISATION OF LARGE PERMANENT SALT LAKES

The salinity of many of the world's largest and permanent salt lakes is presently rising due to human activities (Williams 1993, 1996). In Mono Lake (California), it rose from 48 to $90\,g\,L^{-1}$ between 1941 and 1992; in Pyramid Lake (Nevada) it rose from 3.75 to $5.5\,g\,L^{-1}$ between 1933 and 1980; in the Dead Sea (Middle East) it rose from ~ 200 to $> 300\,g\,L^{-1}$ between 1910 and the 1990s; in the Aral Sea (Central Asia) the salinity rose from 10 to $> 30\,g\,L^{-1}$ between 1960 and 1991; in Qinghai Hu (China) it rose from ~ 6 to $12\,g\,L^{-1}$ between the early 1950s and the 1990s; and in Lake Corangamite (Australia) the salinity rose from 35 to $\sim 50\,g\,L^{-1}$ between 1960 and the early 1990s. In a few lakes, notably the Caspian, the salinity has either remained stable or fallen slightly.

The core reason for the rises in salinity in almost all cases (increases in natural aridity may be implicated in at least one case) is the diversion of inflowing river waters for agriculture and other uses. With decreased inflows, the hydrological balance is changed and lake volume decreases with consequent rises in salinity, since the salt mass remains more or less constant.

The effects are many and vary between lakes according to the nature of the lake basin, the volume of water diverted, and initial conditions in the lake. An extreme example is provided by the Aral Sea (Fig. 1; Williams & Aladin 1991; Letolle & Mainguet 1993; Glazovsky 1995). Here, rising salinities were accompanied by falling water-levels (> 15 m since 1960), a decreased water surface area, the exposure of extensive areas of the lake bed, the destruction of the archipelago in the south-eastern part of the lake, and marked changes in the biota and biological condition of the lake. An increase in the frequency of dust storms and a decrease in agricultural productivity surrounding the lake (because of salt deposition) also developed. Not all such consequences have followed the secondary salinisation of other large salt lakes, but falling water-levels and changed biological conditions are always a consequence.

The cost of changes in the Aral Sea have been enormous at all levels. A first cost was the loss of the south-eastern archipelago, which had had a high conservation value as a habitat for both local wildlife and migrant waterfowl. Increased salinity led to the demise of the economically and socially important fishery. Other costs were to transportation and human health; the lake could no longer be used for shipping; and respiratory and other human illnesses increased in frequency. Not least in the minds of many local people, the Aral lost much of its aesthetic and cultural value. Not all losses of this sort (or to the same extent) have taken place in other large salt lakes from which water has been diverted. Even so, there is no doubt that, overall, the salinisation of the world's largest salt lakes has resulted in serious economic, social, conservation and environmental losses. How these losses compare with the benefits gained from the river waters diverted depends upon the perspective taken. Economic benefits may be greater than economic losses, but this is certainly not so from the conservation and environmental perspective.

Fig. 1. Edge of Aral Sea at Barsakelmes Island, May 1990. The water has receded a good deal since 1990.

The most obvious management response to present and continued salinisation is to restrict river diversions. To implement restrictions needs both clear recognition of the losses involved if diversions continue, and actions to compensate for the decreased availability of diverted water. These are not easily achieved but they have been achieved in at least one well-documented case: Mono Lake, California. Here, salinities rose over most of the present century as water was diverted from its inflow streams for use in Los Angeles. This salinisation, however, resulted in the loss of cultural, scenic and conservation values, and after a protracted community and legal campaign and a re-evaluation of the benefit:loss ratio, diversions are presently limited so that the lake salinity has now more or less stabilized. Limitations on diversions will continue until the water-level (and thus salinity) reaches pre-1940 levels.

Despite the examples provided by the Aral Sea and other salt lakes, schemes to divert water from salt lakes are still being proposed (and implemented). One that would result in an immense loss to conservation values is the scheme to divert water from the Mar Chiquita, a large salt lake in northern Argentina (Reati *et al.* 1997). This lake provides a feeding and refuge site for large numbers of migrant birds (~ 500 000 annually) and is part of the Western Hemisphere Shorebird Reserve Network. Many other losses would occur if the scheme were implemented.

FRESHWATER LAKES AND WETLANDS

Many freshwater lakes and wetlands occur in semi-arid, if not arid, regions. Major changes in land use have taken place in such regions and these have frequently led to increased salinities in run-off following salt mobilization in subsurface waters. The most important human activities in this connection are the clearance of natural vegetation (deforestation) and irrigation.

Many examples have been documented in Australia. Thus, in south-western Australia, many formerly freshwater lakes and wetlands have become saline after catchments were cleared of deep-rooted vegetation with high transpiration rates (mostly trees), and replaced with shallow-rooted crops with lower rates of transpiration. Underlying water-tables rose as a result and, when near the surface, capillary action led to surface deposition of salts after evaporation. These salts leached into waters within catchments and ultimately reached freshwater lakes and wetlands, so beginning their salinisation. Lake Toolibin is the last remaining significant freshwater wetland within a large region of south-western Australia (Boulton & Brock 1999), and even this is threatened despite strong efforts to maintain it as a freshwater body.

A similar fate awaits many wetlands on the River Murray floodplain in south-eastern Australia. Here, both catchment clearance (dryland salinity) and irrigation have elevated the subsurface saline aquifer. This is now at or near the surface in many places, and salinizing floodplain wetlands (Macumber 1991).

Cases are less well-documented outside Australia, but several are known. In Egypt, Lake Qarun, south-west of Cairo, has changed from a freshwater lake to a saline basin because of salt inflows in drainage water from surrounding agricultural lands (Saad & Hemeda 1999). Similarly, increases in the salinity of some freshwater Ethiopian rift valley lakes has occurred in the past three decades, a change attributed to irrigation, diversions and deforestation (Gebre-Mariam 1999).

The effects of even small rises in the salinity of fresh waters can be profound because the halotolerance of the freshwater biota is more limited than the biota of salt lakes. A frequent and most obvious initial effect is the disappearance of macrophytes and riparian trees. Indeed, one of the clearest indications that a saline water-body has arisen from the salinisation of a freshwater one is the presence of dead trees within the boundaries of the lake (Fig. 2). The overall biological response to increased salinity is a decrease in biodiversity and the replacement of the halosensitive biota with a halotolerant one.

The costs of salinizing freshwater lakes and wetlands, as with saline lakes, are many and varied. Economic losses obviously include a loss in their ability to serve as supplies for domestic, agricultural and other uses. Further losses, for example to conservation and to the environment, are less obvious but nonetheless substantial. In the case of wetlands on river floodplains, losses will include degradation of the riverine ecosystem as a whole because floodplain wetlands and their associated rivers function in a mutually interdependent way (Davies *et al.* 1994). These losses do not

Fig. 2. Lake Tallinga, South Australia. Note the dead *Melaleuca* remnants in the centre of the lake, a clear indication that this salt water-body was once fresh.

include agricultural losses due to salinisation. No firm global figure can be given for these, but note that by 1990 between 80 and 110 million ha of irrigated land was affected by salinisation to some degree (34–47% of all irrigated land; FAO 1990). More recently, Ghassemi *et al.* (1995) have noted the impact of salinisation on agricultural land in a number of dryland countries (and, at the same time but without details, commented on the increasing significance of salinisation to water resources).

Management responses are of several sorts. Stopping vegetation clearances, restricting dryland agriculture, and tree replanting are essential to protect freshwater lakes and wetlands from further salinisation. Certainly, it is integrated catchment management rather than the management of salinized waters that needs to be emphasized, because the rehabilitation and management of waters already salinized is much more difficult, and often perhaps not possible.

For floodplain wetlands threatened by rising saline groundwaters, management schemes already in operation involve lowering water-tables by pumping. The problem then is where and when to dispose of the saline wastewater. Disposal underground is the best option, but saline wastewater is often stored either in low-lying areas near the river or in natural water-bodies (which are then degraded). Such salt storage basins (so-called evaporation or recharge basins) have been used in a number of places as a means of managing salinisation but can at best be viewed only as a short-term solution. They may also give rise to additional problems as, for example, in California, where many concentrate selenium, a toxic element which impacts on local waterfowl populations. The number of evaporation basins on the River Murray floodplain in Australia is already more than 200 (Evans 1989). Despite some values as wetlands (Roberts 1995), they are highly unnatural bodies of salt water and are of little value overall.

The salinisation of freshwater lakes and wetlands is most important in semi-arid regions, but, as indicated, is not confined to them. Passing note may be made of how saline groundwaters are salinizing waters (voids) in former opencast coal mines in Germany (Bohrer *et al.* 1998), and how underground salt mining has caused salinisation of several Cheshire meres ('flashes') in England. The salinisation of coastal rice fields following the abandonment of prawn aquaculture is regarded as a major threat to the viability of the rice-growing industry in Thailand (K. F. Walker, pers. comm. 1999).

RIVERS AND STREAMS

The salinisation of rivers and streams is closely associated with the salinisation of freshwater lakes and wetlands because they either arise in salinized catchments and discharge their salt loads into these water-bodies, or flow from (or are intermittently connected with) them and carry an additional salt load as a result. Not only are small streams and rivers involved in this way: some large rivers are too, most of which, of course, are allogenic and gain salt only during passage through semi-arid and arid regions. Whatever the case, the salinisation of running waters in many drylands is already occurring, and salinities will increase further in the future. Williams (1987) drew attention to the hazard to running waters posed by salinisation over a decade ago, and others have done so more recently. Davies and Day (1998) regard salinisation of rivers as one of the major threats to South Africa's water resources.

A well-documented case of a river that has been salinized by catchment changes is provided by the Blackwood River in south-western Australia. This river drains a large catchment that has been extensively cleared of natural vegetation to allow for agriculture. Before 1910, the river had a salinity that was sufficiently low for it to be used as a supply for steam locomotives (< 0.5 g L^{-1}). In the intervening decades, it rose gradually so that now most of it has a salinity of > 3 g L^{-1}, and the river displays a reversed longitudinal profile with salinities higher in the upper reaches (> 10 g L^{-1}) than in the lower ones. This is the opposite of the usual profile.

An equally striking example of increased river salinities caused by anthropogenic activities is provided by the rivers that discharge into the Aral Sea, the Syr and Amu darya (Fig. 3). Data for the Syr Darya are given in Table 1 for one station on this river between 1912 and 1997–98. It can be seen that the salinity of the river has increased by seven-fold between these dates. In many cases, river salinities will reach or have reached levels that render them useless for certain economic purposes (e.g. irrigation). This is the case in the examples given.

Fig. 3. Syr Darya near Kyzl Orda, June 1991.

Little need be written about the causes of river and stream salinisation because they are ultimately the same as those leading to the salinisation of freshwater lakes and wetlands: notably, changes in catchment land-use and irrigation. Mining, with the discharge of brines to rivers, is sometimes important, and even large rivers in temperate regions may be salinized in this way (e.g. the River Werra in Germany; Schmitz 1956).

Again, the ecological effects of salinisation in rivers and streams are by and large the same as those in freshwater lakes and wetlands; a decrease in biodiversity and the development of a halotolerant biota. Changes to the biota, however, are less easily separated from those impacts which follow the other two major anthropogenic disturbances that are of particular significance in semi-arid rivers and streams, namely, flow regulation (by impoundment) and diversion.

The economic costs of river salinisation are significant, particularly when the rivers involved provide the only permanent and reliable sources of water. When salinities reach 1 g L^{-1} they generally render the water useless for most agricultural purposes, and only slightly higher salinities make the water useless for most other economic purposes (drinking by humans, industrial supplies). Since most dryland rivers have salinities not much less than 1 g L^{-1}, it is clear that relatively small changes in river salinities have large impacts upon their economic usefulness. It is not surprising that managers become increasingly alarmed at even small rises (as they have, for example, in the River Murray, Australia; Williamson *et al.* 1997). Note too in this connection that since nearly all semi-arid rivers are now impounded, river salinisation may negate the original purposes of impoundment (often at great expense). Certainly, the US government is finding it expensive to desalinate the Colorado River in order to meet downstream international obligations to supply fresh water to Mexico (Stanford & Ward 1986).

Salinity increases of economic significance in rivers may not impact other riverine values to the same extent, because much of the biota may have already developed a tolerance to small natural fluctuations in salinity. The extent and importance of this natural halotolerance remains largely

Table 1. Salinity of Syr Darya at Kazalinsk between 1912 and 1997/98

Year	1912	1940	1950	1960	1970	1980	1985	1997/8
Salinity (g L^{-1})	0.37	0.36	0.52	0.95	1.01	1.72	2.26	2.45–2.75

Data from Letolle and Chesterikoff (in press).

indeterminate for most rivers, but recent work suggests that it is lower than was originally thought, so that the ecological, environmental and conservation costs of river salinisation should not be underestimated. Certainly, changes in macroinvertebrate community structure in some Australian rivers appears to be attributable to rather small differences in salinity (Kefford 1998).

Several strategies are used to manage river salinisation; many, it must be noted, are of rather short-term value. They include both prophylactic and remedial measures. The former aim to prevent further salinisation, and focus on efforts to decrease salt discharges from salinized catchments and rising water-tables. Remedial strategies aim to decrease or contain river salinities, or at least manage the discharge of saline wastewater into them (or the withdrawal of useful water from them), in such a way that potential impacts on values are minimized. Salinity management involves an integrated catchment-wide approach incorporating knowledge of the effects of flow regime alteration, regulation of diffuse and point sources of saline water, and the adoption of appropriate land-use and water management practices. The development of stream salinity models with predictive power has been useful in this respect.

CONCLUSIONS

The foregoing discussion indicates that secondary salinisation is now a significant process impacting upon water resources in almost one-third of the world's land area. The extent of its impact is likely to increase, not least because of global climatic change.

The major causes are river diversions, changed land-use practices and irrigation. These have resulted in increased salinities in surface waters, rises in the levels of water-tables, the mobilization of subsurface salt, and the redistribution of surface salt. The effects are adverse and mostly irreversible. Overall, they lead to decreased biodiversity, and significant economic, social and environmental losses. Economic costs are of particular concern because unsalinized water (i.e. fresh water) in drylands is the most important natural resource in shortest supply.

Salinisation can be contained only by informed water resource management. Without this, the prognosis for water resources in many semi-arid and arid regions is bleak. There will be no less water available but its value will be seriously degraded and impaired, perhaps to the point when its presence is no more than an historical remnant of past, more favourable times.

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