

Water salinization and shorebirds: emerging issues

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Salinity from agricultural drainwater, surface flow and subsurface flow is a problem in at least some inland wetlands in every western state in the United States. Water salinization is a particularly insidious threat to waterbird populations because wetland quality may not visibly decline until the problem is advanced. In this paper we review 1) evidence that salinization is an important management problem in inland wetlands, 2) means available to shorebirds to cope with salinity, 3) mechanisms by which the costs of salinization are likely to reduce shorebird reproductive success, and 4) how salinization modifies structure and diversity of ecosystems. Finally, 5) we discuss emerging management concerns with respect to reducing or eliminating salinization effects on shorebird populations.

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Introduction

The art and science of habitat management revolves around the control and enhancement of habitat quality (cf. Reed 1995). A management plan for shorebirds advocates manipulating controllable habitat factors in order to provide the best habitat quality possible for shorebirds (Helmers 1992). The working definition of habitat quality currently seems to be "that which results in the greatest number of birds" (e.g., Merendino *et al.* 1992), or, more rarely, "that which results in the greatest diversity of species" (e.g., Boshoff & Piper 1992). Although these may be meaningful management goals on short time scales, for conservation purposes only those aspects of habitat quality that help maintain diverse populations over large time scales are of significance (Karr 1993; Suter 1993; Noss & Murphy 1995).

Numbers of birds present, or even breeding, in a wetland on short time scales are *not* necessarily indices of the contribution of habitat quality to the maintenance of populations. For instance, because so much wetland habitat has been destroyed (Frayer *et al.* 1989; Dahl 1990), shorebirds may breed in large numbers in wetlands of very poor quality. One very dramatic example of this phenomenon was Kesterson National Wildlife Refuge, in the San Joaquin Valley of California. Kesterson was a wetland supplied with irrigation drainwater from the Westlands Water District. Large numbers of wading birds bred at Kesterson, and the project was viewed initially as a habitat-replacement success. Nonetheless, these birds failed to reproduce successfully (Williams *et al.* 1989) because drainwater supplying the wetland was contaminated with

selenium and other heavy metals, concentrated through soil leaching and water recycling (Ohlendorf *et al.* 1986, 1989). Bioaccumulation of these toxicants resulted in low hatchability of eggs, and dramatic malformations (Hoffman *et al.* 1988) and subsequent death of those chicks that did hatch (Ohlendorf *et al.* 1989). In other words, although Kesterson received a great deal of *use*, it was habitat of very low *quality*. Kesterson has since been filled with uncontaminated soil in order to displace breeding birds to wetlands of better habitat quality, and habitat managers are monitoring potential bioaccumulation through the new terrestrial food chain (Wu *et al.* 1995).

There is an equally dangerous, potentially much more widespread, mechanism of wetland water quality reduction: water salinization. Water salinization is a particularly insidious threat to waterbird populations because wetland quality may not visibly decline until the problem is advanced.

Salinization may result in reduced reproduction through chick mortality, while reduced vigor associated with dehydration may increase mortality at all life stages. In this paper we review 1) evidence that salinization is an important management problem in inland wetlands, 2) means available to shorebirds to cope with salinity, 3) mechanisms by which the costs of salinization are likely to reduce shorebird reproductive success, and 4) how salinization modifies structure and diversity of ecosystems. Finally, 5) we discuss possible management techniques for reducing or eliminating salinization effects on shorebird populations. This paper is *not* presented as a definitive discussion of the cure for wetland water salinization. Our goals, rather, are to identify the problem, and generate interest in the process of defining solutions.

Why is salinization a problem in inland wetlands?

Normally, the term *salinity* is taken to mean the concentration of sodium chloride. However, the ion composition of salty water varies widely, and in inland wetlands (the focus of this paper) *salinity* is actually a measure of the total concentration of a number of different ions. The exact combination of ions and minerals in water depends largely on local soil composition and hydrology of surface and ground water.

In arid lands, where salinization is most common, soils naturally contain variable amounts of sodium, potassium, and other mineral salts, but also magnesium, carbonate, bicarbonate, sulfate, boron, fluoride, arsenic, and selenium. Hence, in arid lands, wetlands and other bodies of water are frequently naturally salty (and significantly alkaline) as a function of the processes of runoff and evaporation over geologic time. For instance, Mono Lake in California and the Great Salt Lake in Utah (two significant sites for shorebirds; Oring & Reed, this volume) are both natural saline lakes. For the purposes of this discussion, *we will use the term salinization to mean anthropogenically-caused increases in water salinity (defined very broadly as increases in conductivity of a particular wetland or body of water, without restriction to any particular ion composition) on relatively short time scales, even in cases where some degree of salinity was present naturally.* In considering larger spatial scales, we also will use the term to imply the decrease in relative availability of fresh water in a landscape.

Globally, salinization is common everywhere agriculture is conducted on arid lands, e.g. north Africa, southern and western Asia, central Australia,

and virtually all of the Middle East (Waisel 1972; Figure 1). In North America, salinity from agricultural drainwater, surface flow and subsurface flow is a problem in at least some inland wetlands in every western state in the U.S. (U.S. Fish and Wildlife Service 1992) (Figure 2). Salinization is particularly acute in the Great Basin, and in parts of California, Arizona, New Mexico and Texas, where growing human populations and agriculture compete for limited water, and where most wetlands are downstream from urban and agricultural users (El-Ashry & Gibbons 1988). Increasingly, solutions to these conflicts involve multiple use and reuse of water, resulting in increased salinity of water at agricultural sites, and subsequently, at terminal wetlands. Salinization is already a problem at many of the world's most important shorebird sites. Sites declared of hemispheric or international importance to shorebirds by the Western Hemisphere Shorebird Reserve Network in the Great Basin include Mono Lake, Great Salt Lake and Stillwater/Carson Lake (WHSRN 1992) and all have suffered significant degrees of salinization (Patten *et al.* 1987; Woolf 1993; Lico 1992). (Unfortunately, although reserve designation by the Western Hemisphere Shorebird Reserve Network (WHSRN) draws much-needed attention to sites of importance to shorebirds, it provides no concrete means of protection, particularly against the gradual degradation of water quality.)

In the arid American west, many factors tend to increase the salinity of inland wetlands. Increased urban use of riverine waters decreases the amount and quality of water available for terminal wetlands. Effects of such decreases are twofold: 1) some wetlands dry up, reducing freshwater and the total number of wetlands available in the landscape, and 2) remaining wetlands become more shallow and

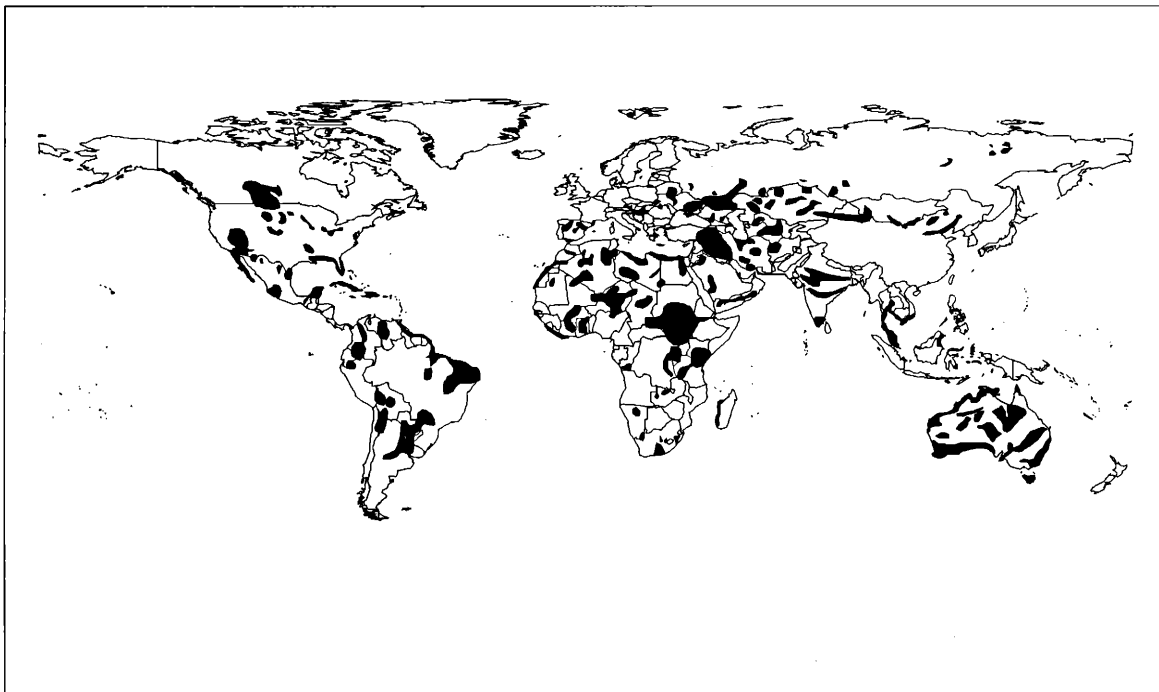


Figure 1. Global distribution of salt-affected soils (and hence water), and areas with the potential for water and soil salinity problems (adapted from American Society of Civil Engineers 1990).

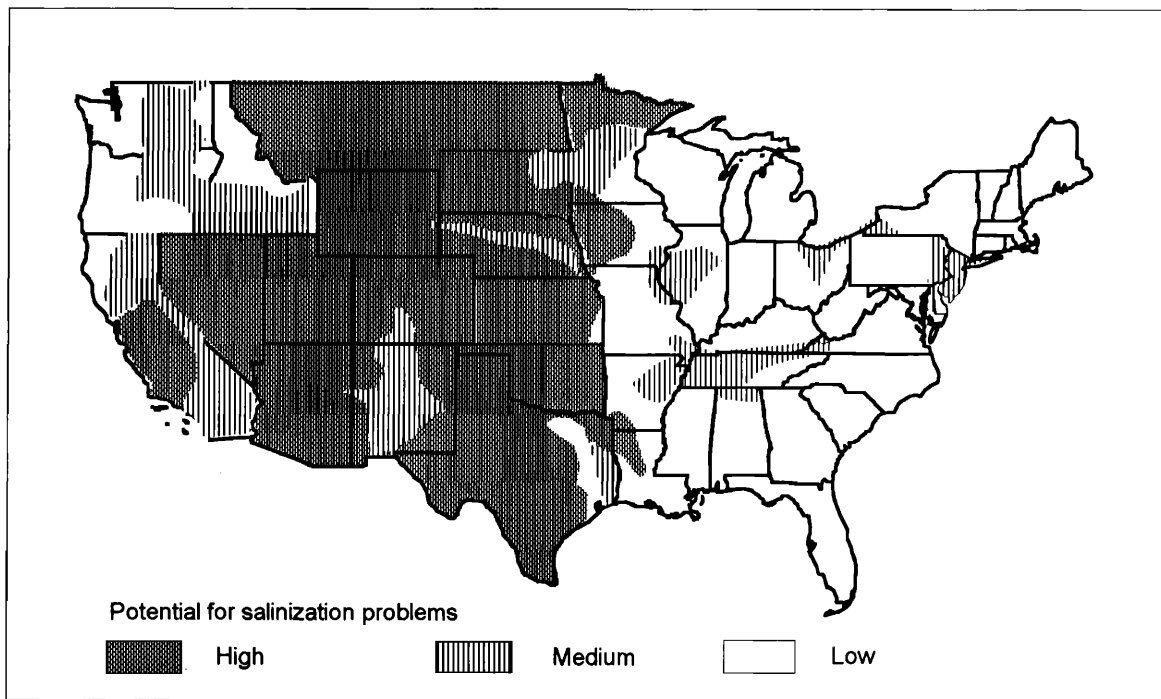


Figure 2. Areas in the conterminous United States with the potential for water and soil salinity problems (adapted from American Society of Civil Engineers 1990; note that coverage for North America differs from Figure 1 because of differing definitions of risk).

more saline through evaporative concentration. For example, water diversions of eastern Sierra Nevada snow melt by the city of Los Angeles have, over the last century, caused Owens Lake to disappear completely, and Mono Lake to drop more than 40 vertical feet while tripling in salinity (Patten *et al.* 1987). Both of these naturally-occurring saline lakes were formerly ringed with freshwater wetlands, which no longer exist at Owens, and are reduced enough at Mono to have virtually eliminated the hundreds of thousands of ducks once found there (State of California 1994a).

Public desire for recreational water in an arid landscape encourages freshwater impoundments, preventing freshwater inflow into already saline wetlands. For example, a controversial proposal to separate Farmington Bay from the Great Salt would eliminate freshwater flows into that part of the lake, replacing mesosaline emergent wetlands with a freshwater reservoir designed to provide drinking water as well as recreational income for Salt Lake City suburbs (Woolf 1993). If this plan were implemented, 200 km² of emergent wetland would be lost under the reservoir itself, while hypersaline lake waters would become even more saline because of reduced freshwater input. Diversions of this kind are likely to exacerbate concentration of ions by evaporation. As the body of water shrinks, the surface-to-volume ratio increases, accelerating the rate of evaporation. In most cases, surface-to-volume ratios are already high because of the initial shallowness of most inland wetlands. Also, urban water reuse, such as the use of "grey" water for watering lawns and decorative plantings, can increase salinity by 325 mg/l/cycle (Bunch &

Ettinger 1964). City sewage reuse can lead to groundwater salinization (Bagley 1967).

Agricultural multiple-use, and enforcement of irrigation conservation programs, also decreases the quality of water in inland wetlands. Federal legislation designed to end water disputes over the Newlands Irrigation Project of western Nevada and northeastern California (Public Law 101-618, 1990), reallocated water away from the project to protect endangered fish at Pyramid Lake. Legislation also mandated more efficient water use by the irrigation district. However, spillage reduction associated with more efficient irrigation operations would *double* concentrations of salts and heavy metals in surface and subsurface flows reaching Stillwater National Wildlife Refuge and nearby shallow wetlands (U.S. Dept. Interior 1988).

Much attention has rightly been paid to the dramatic effects of heavy metal bioaccumulation on wetland birds (*e.g.*, Hothem & Ohlendorf 1989; Scheuhammer 1991; Skorupa & Ohlendorf 1991); much less has been directed at the consequences of salt concentration on these animals. Salinization is more likely to be ubiquitous, and is liable to be a problem everywhere toxicants are accumulated by leaching and runoff. In contrast, there is a huge literature on salinization effects on plants, extending to worldwide efforts to produce salt-tolerant hybrids for agriculture. In some parts of the world, these efforts are directed at making salt water irrigation possible (National Research Council 1990). The eventual effect of such activities on terminal wetlands in arid lands and their bird populations would be extreme.

Table 1. Mean relative salt gland masses for shorebirds.

<i>Species</i>	<i>Mass of both glands (in g/g body mass)</i>	<i>Classification¹/ Conditions at time of sampling</i>	<i>Source</i>
Green Sandpiper <i>Tringa ochropus</i>	0.01	Freshwater	Staaland 1967
Wood Sandpiper <i>T. glareola</i>	0.02	Freshwater	Staaland 1967
Common Snipe <i>Gallinago gallinago</i>	0.02	Freshwater	Staaland 1967
Great Golden Plover <i>Pluvialis apricaria</i>	0.03	Freshwater	Staaland 1967
Bar-tailed Godwit <i>Limosa lapponica</i>	0.05	Marine, except during breeding	Staaland 1967
Dunlin <i>Calidris alpina</i>	0.08	Marine, except during breeding	Staaland 1967
Little Stint <i>C. minuta</i>	0.08	Marine, except during breeding	Staaland 1967
Sanderling <i>C. alba</i>	0.11	Marine, except during breeding	Staaland 1967
Red Knot <i>C. canutus</i>	0.12	Marine, except during breeding	Staaland 1967
	0.15 (estimated from graph)	Wild caught coastally	Piersma 1994
	0.05 (estimated from graph)	Captive, freshwater acclimated	Piersma 1994
Common Sandpiper <i>Actitis hypoleucos</i>	0.06	Adults- freshwater and marine	Staaland 1967
	0.08	Chicks- caught at freshwater	Staaland 1967
Ringed Plover <i>Charadrius hiaticula</i>	0.07	Freshwater and marine	Staaland 1967
American Avocet <i>Recurvirostra americana</i>	0.04	Collected at hypersaline lakes	Mahoney & Jehl 1985
Wilson's Phalarope <i>Phalaropus tricolor</i>	0.04	Collected at hypersaline lakes	Mahoney & Jehl 1985

¹Classifications are those used by Staaland (1967). For all other sources, conditions under which the samples were collected are given.

How does salinity affect shorebird populations?

Direct effects - osmoregulation and maintenance of water balance

Birds, like other vertebrates, filter solutes, such as salts, out of their bloodstream by means of kidneys. Although the formation of uric acid is less water-consumptive than the formation of urea, avian kidneys are less effective at concentrating solutes than are mammalian kidneys (Schmidt-Nielsen 1970; Skadhauge 1981). When drinking salty water, birds cannot maintain water balance through renal excretion alone (Willoughby & Peaker 1979). Because cellular metabolism depends on sufficient quantities of water, and nerve and muscle function on ion ratios with narrow margins of variability, dehydration affects every system in the body. Extreme dehydration can lead rapidly to death.

In the struggle to maintain water balance, birds have in their arsenal paired supraorbital, or nasal, salt glands. It has been recognized since 1667 (Comelin; see Technau 1936 as cited in Cooch 1964) that the enlargement of these glands was associated with saline habitats (Heinroth & Heinroth, 1926-1928; Schildmacher, 1932; both as cited in Cooch 1964). Schmidt-Nielsen and colleagues (Schmidt-Nielsen

1960; Schmidt-Nielsen *et al.* 1957; Schmidt-Nielsen & Fange 1958; Schmidt-Nielsen & Sladen 1958; Schmidt-Nielsen & Kim 1964) were first to correctly assess the salt-excreting function of the gland.

The avian salt gland functions in osmoregulation by responding to increases in plasma osmolality and volume. Excretion by the gland is controlled through the central nervous system, with osmolality and pressure receptors in the heart and elsewhere. When glands are active they secrete a fluid containing NaCl that is hyperosmotic to blood plasma. This secretion is directed via ducts to the nasal cavities; fluid emerges from the nares where it drips, or is forcibly shaken, off the beak (see Holmes & Phillips 1985 for review of the secretion process). The mechanism by which salt is concentrated in salt gland secretions has been much studied (see Skadhauge 1981; Holmes & Phillips 1985 for reviews). In brief, it involves active transport of Na⁺ and Cl⁻ ions across cell membranes, and is thus an energy-consumptive process.

Salt gland function in birds is tightly correlated with saline habitats and salty diets. Salt glands are large and fully functional in birds using marine habitats (especially those eating invertebrates that are isotonic with surrounding seawater) while the gland is small and dormant in most terrestrial and freshwater birds (summarized in Holmes *et al.* 1961). In many species, activity and development of the gland can be

stimulated by continuous exposure to saline water (Table 1 summarizes all available shorebird data).

Although we know that marine birds possess salt glands competent to maintain water balance, the picture is less clear for shorebirds and other wading birds, especially for those breeding at or migrating through inland wetlands. First, we have less information about osmoregulation and salt gland function in shorebirds than in other species. Of the 155 citations in Holmes & Phillips' (1985) review, only one (Staaland 1968) refers to shorebirds. Second, the data that exist for shorebirds are equivocal with respect to whether salt glands in shorebirds, if stimulated, allow acclimation to salty habitats. Few published studies examine salt gland function in shorebirds. Staaland (1967, 1968) examined 14 European shorebird species and concluded on the basis of small gland size and experimental salt-loading that several species (Green Sandpiper, Common Snipe, and Wood Sandpiper) are poorly adapted to excrete excess salt (Staaland 1968). However, these experiments were conducted with freshly caught birds, and so offer no information about the possible ability of the species studied to acclimate over time through salt gland enlargement. Piersma (1994) found that captive Red Knots that were acclimated to freshwater had much reduced relative (mass-specific) salt gland sizes compared to wild-caught Red Knots, indicating atrophy of the glands when salt stress was removed. It is possible that a few species of shorebirds may have no salt glands at all: Maclean (1977) reported that he was unable to locate salt glands in a single specimen of Red-kneed Dotterel (*Charadrius cinctus*).

Other investigators did not examine salt glands directly, but examined the ability of shorebirds to acclimate to salty drinking water in captivity. Purdue & Haines (1977) found that Snowy Plovers (*Charadrius alexandrinus*), Killdeer (*C. vociferus*), and Semipalmated Sandpipers (*Calidris pusilla*) had limited abilities to acclimate. Tolerance of acclimated Snowy Plovers and Semipalmated Sandpipers extended to 0.3 M (50% sea water). They suggested that Snowy Plovers maintain water balance on their salt plain breeding grounds by not consuming salt water, eating insects with high freshwater contents, and through water-conserving thermoregulatory behaviors, such as standing in pools during hot weather. Klassen & Ens (1990) showed that captive freshwater-acclimated Red Knots were capable of acclimating back to seawater.

Mahoney & Jehl (1985) examined stomach content and blood plasma osmolality, as well as salt glands and suggested that Wilson's Phalaropes and American Avocets avoided swallowing salt water by straining their prey. This raised the possibility that the need for salt gland competence (and hence freshwater in managed wetlands) might be obviated in some species by behavioral and mechanical means of salt avoidance. However, shorebirds able to avoid swallowing salt water would still eventually need to obtain water with low osmolality, either from prey or elsewhere, to balance water lost evaporatively or through excretion of nitrogenous wastes.

Although avocets at Mono Lake [one of Mahoney & Jehl's (1985) study sites] are consuming invertebrate

prey that are hypotonic to hypersaline lake water, these prey are still (relative to freshwater) salty (about 50% seawater). This is liable to be more of a problem in hypersaline systems than in those that are less salinized. Indeed, although Mahoney & Jehl (1985) found no differences in salt gland sizes among birds at different lakes, mean relative salt gland size was 0.04, equivalent to the low end of Staaland's (1967) data for strictly marine birds. In addition, their data show that both avocets and phalaropes are maintaining blood serum osmolalities up to 200 mOsm/kg below those of their prey at Mono Lake. Both these species and other shorebirds [Red-necked Phalaropes (*Phalaropus lobatus*), Western Sandpipers (*Calidris mauri*), Least Sandpipers (*C. minutilla*)] at Mono Lake travel regularly to fresh water sources around the lake shore and inland, where they can be seen vigorously bathing and drinking. The importance of access to freshwater at Mono Lake is attested to by the huge flocks (up to 20,000 birds at a time) visiting Rush Creek, a major freshwater inflow on the south shore of the lake, bathing, drinking, and departing again, all within the space of 2 hours (M. Rubega, pers. obs.). Furthermore, the lakes at which Mahoney and Jehl collected data ranged from oligosaline Lake Abert [salty enough to contain brine shrimp (*Artemia monica*) and brine flies (*Ephydra hians*), along with other, less salt-tolerant prey] to hypersaline Great Salt Lake (salty enough to contain nothing but brine shrimp and brine flies), but did not include a freshwater lake. They may have found no differences in salt gland size among lakes because they were looking at enlarged glands at all lakes.

Indirect effects - costs of behavioral avoidance of salt loading

The most obvious way for shorebirds to avoid salty wetlands is to make use of sites that are relatively fresh. However, if Great Basin wetlands suffer salinization on large spatial scales, such freshwater sites will become fewer and farther between, and increasing investments in time and energy traveling between wetlands will be required in order to locate them. For breeding shorebirds, such searches may also represent a further cost in reduction of time and energy available for breeding. Furthermore, as freshwater wetlands become more scarce, some birds will have no choice but to settle, for some length of time, in salinized ones.

As we have already noted, saline systems are often highly productive. The importance of that observation for shorebirds is attested to by the fact that large (but not very diverse) populations of breeding and migratory shorebirds are already found at the most saline lakes in the Great Basin (e.g., Neel & Henry, this volume). However, in all these cases freshwater inflows are available nearby, and shorebirds are known to use them. Use of freshwater in these cases is not exclusively for drinking; shorebirds visiting freshwater sources at Mono Lake bathe vigorously (M. Rubega, pers. obs.). Because the waterproofing of waterbird feathers depends on the interaction of feather structure with surface tension in water (Rijke 1970), and surface tension decreases with increasing solutes (Streeter & Wylie 1979), saline water probably increases feather wetting. Wet plumage can increase

thermoregulatory costs significantly. [Although summer daytime temperatures in the Great Basin are high, consider the fact that nighttime temperatures may fall by more than 30° F (17.2° C), wind is frequent, and birds are defending relatively high core temperatures.] Alternatively, feather wetting may lead to the need to preen more frequently, for longer periods of time, reducing time and energy available for other activities, such as foraging.

How will salinization affect shorebird reproduction?

In light of the increasing threat of salinization of inland wetlands, the relative paucity of direct information about the ability of shorebirds to maintain water balance is troubling. From the point of view of those managing wetlands for breeding shorebirds, the absolute absence of information on the abilities of hatchling shorebirds to do so is a genuine threat to shorebird populations. In general, birds are most vulnerable during the chick life stage (Lack 1954; Wunderle 1991). Chicks are small in size, have high metabolic rates (and hence higher water turnover rates than adults, as well as a greater percentage of body mass as water) and are undergoing rapid physical and associated behavioral development. Even precocial species are relatively immobile in comparison to adults, which can readily fly periodically to freshwater sites, or desert a salinized wetland altogether. Reductions of surface tension in saline water may cause feather wetting (M. Rubega, pers. obs.). The resulting heat loss may be a particularly serious problem for the youngest age classes of chicks because most species are not fully endothermic at hatch (Cramp & Simmons 1982). Also, although adults may be able to strain their prey from salt water and thus reduce intake of salty water, chicks may lack the bill structures necessary to do so until late in development. It is important to note that adult shorebirds are not infallible in their choice of breeding habitat. The high mortality and morbidity rates of offspring at Kesterson NWR (which, in addition to high concentrations of selenium, contains highly salinized water) attest to this fact.

The few previous studies of salt tolerance in other groups of hatchling waterbirds indicate that salinity is likely to be a serious problem for hatchlings. In a survey of 39 species of Australian waterbirds, Goodsell (1990) showed that 90% of all brood use of 67 wetlands was in waters with salinities in the fresh to brackish range. Ducklings of several species that breed in fresh or brackish water failed to gain weight normally when exposed to saltwater rearing regimes, and mortality was high in ducklings less than three days old (Ellis *et al.* 1963; Swanson *et al.* 1984; Barnes & Nudds 1991). Ellis *et al.* (1963) concluded that duckling salt glands do not become functional until 6 days of age, but this observation is tempered by the fact that their experiments were initiated with 4 day old ducklings. Swanson *et al.* (1984) and Barnes & Nudds (1991) presented more complete experiments conducted with groups of ducklings of seven species exposed from hatch or 48 hours of age, respectively, to four saltwater regimes. In both cases, interspecific variability in growth reduction and mortality were

significant. Neither research group investigated the mechanisms through which salt loading impaired growth in the treatments in which mortality was not complete. It seems apparent, however, that salt glands in ducks are not sufficiently competent in the youngest age classes to maintain water balance. Furthermore, sublethal growth affects which might influence survival to fledging and beyond are a significant concern.

Bildstein and his colleagues (Johnston & Bildstein 1990; DeSanto 1992; Bildstein 1993) showed that nestling White Ibises (*Eudocimus albus*) fail to gain mass and become dehydrated on high-salt diets, even though they exhibited hypertrophy of salt glands, and even though adults tolerate high-salt diets. Presently we lack equivocal information on juveniles of any species of shorebird.

How does salinization affect ecosystems?

Depending on how salty they are, inland saline wetlands may support few or no fish, thus the predominant vertebrates are aquatic birds. Those are generally invertebrate specialists, or generalists capable of subsisting on invertebrates. In general, increasing salinity is associated with decreasing species richness at all trophic levels, although the strength of this effect appears to vary with the scale of measurement (Williams *et al.* 1990). At Mono Lake, only two species of invertebrates are available as prey, but those are extremely abundant. This effect is thought to be due to the heightened productivity of saline waters, and the exclusion of salt-intolerant competitors (Patten *et al.* 1987). Lowered avian diversity at hypersalinized systems, such as Mono Lake, probably results from exclusion of species for which heavy salt loads present an intractable water balance problem (*e.g.*, ducks; see State of California 1994a). Also, those invertebrates remaining in a salinized wetland are likely to be osmoconformers (Kirschner 1979), and, therefore, to have relatively high salt contents (*e.g.*, Phillips *et al.* 1978), exacerbating the need for freshwater among shorebirds feeding in saline systems. At Mono Lake, the known breeding shorebird population consists of only four species (Snowy Plover, Killdeer, American Avocet, and Common Snipe) (Winkler *et al.* 1977), all of whom are found near freshwater seeps and springs, with only another two species (Red-necked and Wilson's phalaropes) maintaining significant migratory populations (Patten *et al.* 1987). All these species are either marine or coastal in distribution during part of their year, or have known historical associations with inland saline systems. We can reasonably expect similar patterns of species persistence among breeding Great Basin shorebirds at salinized wetlands as salinization worsens.

Salinization affects invertebrates, and hence shorebirds, in less obvious ways as well. Salinization leads to the elimination of salt-intolerant emergent vegetation that would provide habitat for some invertebrates (Wolheim & Lovvorn, 1995), altering the invertebrate community, as well as reducing invertebrate variety overall. This reduction in prey species richness has serious implications other than

the exclusion of shorebirds that are specialists on one prey type or another. For growing chicks, lack of prey choices may impair growth and development through the absence of important trace nutrients.

Although salt-tolerant prey may become spectacularly abundant in hypersaline systems, abundance alone is not a measure of diet quality. For example, Rubega & Inouye (1994) showed that adult Red-necked Phalaropes at Mono Lake are incapable of surviving on a diet consisting only of brine shrimp, the more salt tolerant of the two prey species present there (Herbst 1981; Dana & Lenz 1986). For Red-necked Phalaropes, the entire prey base at Mono Lake consists of a single invertebrate species, the brine fly, and that fly would eventually have been eliminated by salinity increases had diversions from the Mono Basin not recently been curtailed (State of California 1994b). Thus, salinity-induced reductions in prey species richness, *per se*, may not necessarily threaten shorebird populations, but the quality and composition of the prey base after salinization will likely limit composition of shorebird communities. This will be particularly true when prey quality is low, and the costs of avoiding salt-loading (or seeking out freshwater to balance it) are high.

Management of salinized wetlands

Water and wildlife managers lack the information necessary to best use available saline and fresh water to its greatest benefit to wildlife. For example, Public Law 101-618 mandates purchases of water rights to maintain wildlife habitat at Stillwater NWR (see Neel & Henry, this volume), but the U.S. Fish & Wildlife Service lacks information necessary to determine the appropriate temporal and spatial scale on which to make freshwater infusions (and hence purchases) in order to make the wetland useful to wildlife (U.S. Fish and Wildlife Service 1992). Until recently, virtually all surface and subsurface water reaching Stillwater National Wildlife Refuge had already been used for irrigation, and that water commonly exceeded Federal "beneficial use" criteria for salinity (Lico 1992), as well as other toxicants.

Little is known about how to appropriately manage saline wetlands for shorebirds. As a consequence wetland managers, whether they realize it or not, are conducting experiments (Elphick, this volume). These experiments, if carefully planned, can provide valuable information about how to make best use of limited freshwater. Toward this end, we discuss below how to measure salinity, characterize what constitutes "acceptable" levels of salinity, and discuss issues of temporal and spatial scale in the relevant measures (Robinson & Warnock, this volume)

Developing target salinities

Measuring wetland salinity is relatively simple (see Table 2), although determining the temporal and spatial scale on which to do so may not be straightforward. Does one measure salinity in a single location in each wetland of interest in order to generate a salinity index, or in multiple locations in order to characterize the degree of salinity heterogeneity (e.g., net-function interpolation, Wu

1992)? Does one measure salinity once a year, or repeatedly? How many wetlands represent the area of concern for the shorebird population of interest? What strategies are advisable when managers only control a small part of the area of interest? For what salinity ranges should we manage wetlands?

We do not have the answers to these questions. Where little information about salinity heterogeneity exists, effective long-term monitoring likely will depend on intensive initial sampling to determine where and how often to monitor. In an ideal world, managers would eliminate sources of salinization, or

Table 2. Classification of types of water (wetlands) with respect to salinity. Modified from Cowardin *et al.* (1979).

Conductivity (S/cm)	Classification
> 60,000	Hypersaline
45,000 - 60,000	Eusaline
30,000 - 45,000	Polysaline
8,000 - 30,000	Mesosaline
800 - 8,000	Oligosaline
< 800	Fresh

dilute salinized water with large volumes of fresh water. In most real cases, the feasible management approach for shorebirds likely will depend largely on the timed provision of limited freshwater inflows to selected salinized wetlands. No data exist that would help us to predict a critical salinity level (e.g., the level at which individual fitness is reduced) even for a single species, even if fine-scale salinity control were possible. Indeed Hurlbert (1991) pointed out that the shape of the curve defining the functional relationship between salinity and the health of populations is a more important and realistic management tool. Susceptibility to salinity may vary widely among species, although current evidence suggests variation among hatchlings may be low.

Setting target salinities depends not only on a better biological understanding of how effects accrue in particular species, but also upon policy decisions about acceptable effects on species richness and at the population level. As a matter of maintaining populations of breeding shorebirds over long time scales, we believe that management of wetland salinization and freshwater inflows depends on measuring, and reducing, costs to chicks. This conjecture is supported by the fact that production of Avocet (*Recurvirostra avocetta*) chicks improved (and has been maintained) in constructed lagoons at Havergate Island, in England, following sluicing with fresher water (Hill 1989) to reduce salinity. Unfortunately, this technique requires the movement of large volumes of water *through* a wetland system, and is not available to managers overseeing terminal wetlands where fresh water is limited.

Temporal and spatial scales of interest

The amount of fresh water needed, and the temporal and spatial scales at which it will need to be applied is currently unknown. As we have already pointed out, chicks are liable to suffer greater effects of wetland water salinity than are adults, and to be more limited in their ability to maintain water balance in a saline environment. Movements

between, or within, wetlands to locate and use freshwater for drinking and bathing will be more difficult for chicks than for adults, and may be energetically more costly. If energetic costs of movement are high, growth may be impaired, with subsequent effects on time to fledging, and hence pre- and post-fledging survival. Also, the distribution of prey as a function of salinity may influence the need to move within and among wetlands, and hence the growth and survival of chicks. Finally, movements over long distances are liable to increase losses to predators.

Therefore, on large spatial scales, maintaining relatively small freshwater inflows close together in multiple salinized wetlands (or in large wetlands) may ameliorate population effects of salt stress more effectively than one high-volume, isolated freshwater inflow in a single wetland. The inverse may be true if a single wetland can provide, e.g., enough suitable nesting sites for the whole population. Because adults are more mobile and less vulnerable than chicks, wetlands sufficiently fresh to allow good chick growth and survival also should provide acceptable adult habitat. If costs of salinization accumulate primarily through direct osmoregulatory routes (*i.e.*, dehydration), then the need for freshwater inflows may be eliminated or reduced post-fledging, when chicks become more mobile and (presumably) have functioning salt glands.

Biomonitoring of avian populations in inland saline wetlands

To provide data for management, salinity and biological monitoring must be coupled. As we have pointed out, simply counting numbers of birds present is not sufficient. Until we have more information about the effects of salinization on shorebird populations, biomonitoring is necessary to assess the success of management treatments. Over time, naturally, our goals should be to identify biomonitoring schemes that are simple, non-labor intensive, and cost-effective. Initially, intensive monitoring will have to be done on individuals, populations (reproductive and migratory), and ecosystems.

At the individual level, it is essential to monitor the growth, behavior and physiological responses of chicks being raised in salinized wetlands. Growth rates provide us with a precise, objective measure of sublethal effects of salinization, and relate (as discussed above) to time-to-fledging, and pre- and post-fledging survival. However, translation of growth rate data into salinity standards requires control data, *i.e.*, comparable data from chicks raised in non-salinized wetlands. Unfortunately, acquisition of growth rate data is labor-intensive, and involves disturbance at a level that may not be acceptable if dealing with endangered or threatened species. For these reasons, monitoring of behavior may prove a more feasible long-term means of monitoring. With enough baseline information, shifts in behavior (*e.g.*, shift in time spent preening at the expense of other behaviors, marked increases or decreases in drinking behaviors, *etc.*) may have great value as hands-off indicators of salinity effects on chicks. This method (at least initially) requires

marked birds, and effort directed at establishing baseline time-budgets. Finally, measures of salt gland size and activity from individuals may provide good indices to salinization, especially in conjunction with growth rate data. Measures of salt gland size require sacrifice of representative individuals from the population of interest, as there is presently no way to estimate salt gland size in a living bird. Again, this may not be acceptable for threatened or endangered species. Until more data are available for shorebirds, Staaland's (1967, 1968) data are the standard for comparison to determine what constitutes enlarged (*i.e.*, salt affected) salt glands. In live animals, frequent head shaking accompanied by fluid sprays or "a runny nose" (dripping bill) are also positive indicators of secreting salt glands.

At the population level, monitoring chick mortality and movement in the landscape in relation to salinity will be particularly important. Comparing reproduction at salinized vs. non-salinized wetlands is critical for setting target salinities. Ideally, field observations of growth rates, pre-fledging mortality, and time-to-fledging can be combined to infer direct and indirect effects of salinization on reproduction. Unfortunately, collecting these data is labor-intensive, and interpretation can be complicated by site differences unrelated to salinity (*e.g.*, disturbance, predation, or other features of water quality).

Other methods of population monitoring might be used as suitable surrogates for detailed observations of reproductive success. Measuring use of freshwater sources in a salinized landscape, for instance, can be accomplished by simple censuses. When combined with salinity monitoring, and an appropriate sampling design (Elphick, this volume), counts of birds at fresh and salinized wetlands can prove an informative monitoring technique. This sort of monitoring is likely to be important for understanding landscape-level effects of salinization, and hence understanding how to manage a single wetland, or a group of wetlands, in relation to the spatial arrangement of freshwater wetlands.

The information value of counts in a sampling design can be verified with intensive short-term studies of marked individuals. Data on the timing and extent of movements of shorebirds (and their broods) among fresh and salinized wetlands would reveal how individual-, population-, and landscape-level factors interact in salinized environments. This information could then be used to revise sampling schemes for improved monitoring efficiency.

At the ecosystem level, it has been shown by other authors (in much greater detail than is possible here, *e.g.*, Patten *et al.* 1987; Aladin & Potts 1992) that salinization alters ecosystems by altering invertebrate communities (Williams *et al.* 1990; U.S. Fish & Wildlife Service 1992; Wolheim & Lovvorn 1995). Salinization affects species composition and population densities (*e.g.*, Dana & Lenž 1986) through direct physiological effects (*e.g.* Herbst 1981), effects on plant communities (Waisel 1972; Aladin & Potts 1992), and hence habitat structure (Wolheim & Lovvorn 1995). Periodic sampling of invertebrate and plant communities to monitor the presence of salt-tolerant insects and/or halophytic plants, especially when coupled with avian species

richness estimates, could provide an index of salinization useful to managers.

Conclusion

Detailed management recommendations will not be possible until more data are available about the costs to shorebirds of living in saline environments. Nonetheless, we believe it is clear that widespread salinization of inland wetlands will have negative effects. Wetland managers can best protect shorebirds by being aware of the problem, recognizing that management efforts in the absence of information *are* experiments, and conducting them (or collaborating with researchers) in a scientifically rigorous manner so as to provide critical data. Finally, managers of inland wetlands can protect shorebird populations by doing anything possible to secure freshwater for wetlands with breeding shorebirds.

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