Review Article

Agriculture and wildlife: ecological implications of subsurface irrigation drainage

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(Received 8 Janua y 1993, accepted 18 Februa y 1993)

Subsurface agricultural irrigation drainage is a wastewater with the potential to severely impact wetlands and wildlife populations. Widespread poisoning of migratory birds by drainwater contaminants has occurred in the western United States and waterfowl populations are threatened in the Pacific and Central flyways. Irrigated agriculture could produce subsurface drainage and wildlife problems in other countries because several of the factors contributing to toxic drainwater in the western U.S.A. (e.g. marine sedimentary basins with soils containing elevated concentrations of trace elements such as selenium and molybdenum; alkaline conditions that favor the formation of water-soluble forms of trace elements; soil salinization problems that require the use of irrigation to flush away excess salts), also occur in other arid regions of the world.

Proposed agricultural irrigation projects should undergo a technical review to assess water demand and supply relationships, and to determine the potential for drainage problems. Environmental assessments should be made at existing irrigation projects to determine if subsurface drainage is present or could occur in the future. Anticipating and evaluating potential problems will allow changes to be made in irrigation practices for the benefit of agriculture and wildlife.

The agricultural demands on water have reduced freshwater inflows and affected the quantity and quality of wetlands throughout the world for decades. Subsurface irrigation drainage is yet another threat to the precarious existence of many wildlife populations.

Keywords: irrigated agriculture; freshwater wetlands; wildlife; fisheries; salinization; soil trace elements; selenium

Introduction

Irrigation is essential to support agricultural production in many arid regions of the world. The intensive irrigation practices necessary to support crops can place high demands on available water supplies and eliminate native wetlands in a short period of time (Frayer *et al.*, 1989; Moore *et al.*, 1990). Wetlands can be lost due to draining, direct conversion to agricultural land, or because water removal from rivers and streams for use in agricultural irrigation robs wetlands of their source of water and they simply dry up. In the western United States wetland losses due to agriculture are severe, and have been occurring for the past 90 years (Preston, 1981; Reisner, 1986; Thompson & Merritt, 1988).

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Because such a small portion of historic wetlands remain in many arid regions (less than 10% in some locations), they are especially valuable as stop-over and wintering grounds for migrating waterfowl and shorebirds, and refuges for resident wildlife populations (Frayer *et* al., 1989). Some of these wetlands have been classified as hemispheric reserves for shorebirds (Thompson & Merritt, 1988), and also support remnant populations of endangered and threatened wildlife, plants, and fishes (Schroeder *et al.*, 1988; Stephens *et* al., 1988; Hoffman *et* al., 1990). In some cases the wetlands are valuable archaeological sites, and have been used to identify and trace human occupancy and culture dating back several thousand years (Raven & Elston, 1988).

Limited availability of water was one of the major obstacles to early settlement of many arid regions (Reisner, 1986). In the United States, the shortage of water, and the perceived need to homestead on, desert lands, led to the establishment of the U.S. Bureau of Reclamation in 1902. The primary mission of this agency was to 'reclaim' unproductive lands by bringing water to arid regions and turning desert into farmland. This reclamation began in earnest with the completion of the Newlands Water Project in Nevada in 1915 and reached a peak with the building of such massive projects as the Hoover Dam on the Colorado River, the California Aqueduct across the Mojave Desert, and the Central Valley Irrigation Project in California (Reisner, 1986). However, the price for this 'reclamation', and associated increase in agricultural production, was a sharp reduction in the amount of water available to native wetlands.

In the early 1980s a new agriculture-related threat to wetlands and wildlife emerged in the United States — subsurface irrigation drainage. This drainage water usually contains elevated concentrations of soil trace elements and other constituents, and has poisoned fish and wildlife populations at several locations (Lemly *et* al., 19943; Presser *et al.*, 1993). These findings raise new questions about the role of irrigated agriculture in the health and ultimate fate of remnant native wetlands in the U.S.A. and other countries. Finding an environmentally acceptable balance for agriculture is more complicated, yet more necessary, than ever before (Moore *et* al., 1990). In order to achieve this balance, it is necessary for water authorities and farmers in arid regions to understand the enviromnental conditions likely to produce toxic subsurface irrigation drainage as well as the hazard this drainage poses to wildlife. This paper is a discussion of how agricultural drainwater has affected wetlands and wildlife resources in the western United States. Environmental conditions responsible for producing subsurface drainage are given, along with implications for agriculture in arid regions of other countries.

Sources and characteristics of subsurface agricultural irrigation drainage

Current agricultural irrigation practices in the western United States use water applications which total about 60-80 cm year^{-1} (State of California, 1990). The amount of water applied is far in excess of what is needed to support crops, but the practice is used to flush away salts that tend to accumulate in crop root zones as evaporation occurs (Moore *et al.*, 1990). Two types of wastewater are produced in the process; surface runoff and subsurface drainage. Surface runoff, also known as irrigation tailwater, occurs because of operational spillage as water is pumped into canals for distribution to fields, or because application rates exceed infiltration rates of the soil. This water can contain high concentrations of pesticides and herbicides if aerial spraying is being done, or if recent land-based applications of these materials has occurred (Neil, 1987; Moore *et al.*, 1990). On-farm water conservation practices tend to minimize surface runoff, and therefore this is usually not a major part of the wastewater generated by agricultural irrigation.

The other type of irrigation wastewater, subsurface drainage, is produced due to a specific set of soil conditions and cannot be eliminated through water conservation. Shallow subsurface (3-10 m) clay lenses or layers impede the vertical and lateral movement of irrigation water as it percolates downward. This results in waterlogging of the crop root zone and subsequent build-up of salts as excess water evaporates from the soil surface. The accumulated subsurface water must be removed in order for crop production to continue (Moore et al., 1990).

Several methods of removing excess shallow groundwater can be employed, including the use of wells and surface canals to forcefully pump and drain the water away. The method of choice in the western United States is to install rows of permeable clay tile or perforated plastic pipe 3-7 m below the surface (Letley et al., 1986). Once these drains are in place, irrigation water can be applied liberally, thus satisfying the needs of crops and also flushing away excess salts. The resultant subsurface wastewater is pumped or allowed to drain into surface canals and ditches, and is eventually discharged into ponds for evaporative disposal, or into creeks and sloughs that are tributaries to major streams and rivers (Moore et al., 1990).

Subsurface irrigation drainage is characterized by alkaline pH, elevated concentrations of salts, trace elements, and nitrogenous compounds, and low concentrations of pesticides (Neil, 1987; Fujii, 1988). The absence of pesticides may appear to be unusual, since surface runoff can contain high concentrations of these chemicals. However, the conditions responsible for producing subsurface drainwater also result in the removal of these potentially toxic compounds. The natural biological and chemical filter provided by the soil effectively degrades and removes pesticides as irrigation water percolates downward to form subsurface drainage (Neil, 1987; Nishimura & Baughman, 1988). At the same time, naturally occurring trace elements in the soil, such as selenium and boron, are leached out under the alkaline, oxidizing conditions prevalent in arid climates and are carried in solution in the drainwater (Presser & Ohlendorf, 1987; Deverel & Millard, 1988).

When subsurface irrigation drainage is discharged into surface waters a variety of serious impacts can occur. The immediate impact is degradation of surface- and groundwater quality through salinization and contamination with toxic or potentially toxic trace elements (e.g. arsenic, boron, chromium, molybdenum, selenium). This water quality degradation can, in turn, affect irrigation, livestock watering, industrial processing, recreational use, and public drinking water supplies. Human health warnings have been issued in some drainwater-affected areas (Zahm, 1986). Elevated concentrations of trace elements in irrigation drainage can severely impact wetlands and poison their fish and wildlife populations (Lemly et al., 1993).

Impacts of subsurface drainage on wildlife in the western United States

In 1985, subsurface irrigation drainage was implicated as the cause of death and deformities in thousands of waterfowl at Kesterson National Wildlife Refuge (NWR) in California (Ohlendorf *et* al., 1986*a*). Naturally occurring trace elements and salts were leached from soils on the west side of the San Joaquin Valley and carried to the refuge in irrigation return flows that were used for wetland management (Zahm, 1986). One of the trace elements, selenium, bioaccumulated in aquatic food-chains and contaminated 500 ha of shallow marshes. Elevated selenium was found in every animal group coming into contact with these wetlands, from fish and birds to insects, frogs, snakes, and mammals (Saiki and Lowe, 1987; Clark, 1987; Ohlendorfet *al.*, 1988*a*). Congenital malformations in young waterbirds were severe, and included missing eyes and feet, protruding brains, and grossly deformed beaks, legs, and wings (Ohlendorfet *al.*, 1986*a*, 1986*b*, 19883; Hoffman *et al.*, 1988). Several species of fish were eliminated and a high frequency (30%) of stillbirths occurred in the single remaining species (Saiki et *al.*, 1991). Laboratory studies conducted by the U.S. Fish and Wildlife Service (USFWS) confi'ied the field assessment that irrigation drainage was the cause of the fish and wildlife problem (Lemly et *al.*, 1993). The poisoned refuge became highly publicized and sparked a great deal of political and scientific controversy (Marshall, 1985; Popkin, 1986; Harris, 1991).

The findings at Kesterson NWR led to a new awareness of the dangers posed by agricultural irrigation drainage. In 1986, the U.S. Department of the Interior (USDOI), the Federal Steward of more than 400 irrigation-drainage facilities and 200 wildlife refuges in the western states (U.S. Bureau of Reclamation, 1981), established a multi-agency program to investigate irrigation-related drainwater problems. This evaluation program is still active and screening-level assessments have been completed at 20 areas in 13 states, which include a total of 20 national wildlife refuges. The western San Joaquin Valley and Kesterson NWR were used as models for identifying and prioritizing potential study areas based on the occurrence of conditions known to contribute to drainwater problems. Samples of water, sediment, and biota (whole-fish, bird liver, bird eggs) were analysed for a variety of trace elements, heavy metals and pesticides, and the results were compared to concentrations known to be toxic to fish and wildlife in experimental studies. Geological and hydrological studies were conducted and, where possible, observations were made to document the occurrence of deformed bird embryos and hatchlings, which is a known marker for selenium poisoning in waterfowl (Hoffman & Heinz, 1988).

Eleven of the 16 study areas at which biota were collected proved to be contaminated with selenium at concentrations that exceed toxicity thresholds for fish and wildlife (Presser et *al.,* 19943). These study areas are spread across nine states from California to Montana and Kansas (Fig. 1). Overt selenium toxicosis (i.e. deformities in bird embryos and hatchlings) was found in five states; California, Utah, Wyoming, Nevada, and Montana. In some cases, these teratogenic effects occurred even though the waterborne concentrations of selenium were below those established by the U.S. Environmental Protection Agency to safeguard aquatic life (Lemly *et al.,* 1993).

Unexplained die-offs of fish and wildlife occurred at Stillwater NWR, Nevada in 1986-7, following a progressive decline in fish and wildlife populations since the 1960s (Rowe & Hoffman, 1987; Thompson & Merritt, 1988). Intensive toxicity studies were conducted by the USFWS at this refuge to evaluate the role of irrigation drainage in the wildlife problems (Finger *et al.,* 1989; Dwyer *et al.,* 1992; Ingersoll *et al.,* 1992). In contrast to Kesterson NWR, where selenium was isolated as the primary constituent of concern, selenium concentrations at Stillwater were very low. The investigations determined that high salinity, trace element contaminants (i.e. arsenic, boron, lithium, molybdenum), and atypical ratios of major ions (i.e. sulfate, magnesium, sodium, chloride, calcium) all acted together to cause toxicity; no single contaminant or water-quality variable was responsible. Subsurface irrigation drainage was found to be a complex effluent whose chemical profile and toxic potential varies both spatially and temporally within a given irrigation area. Rapid, direct mortality may occur in some cases while in others, the effects can be more subtle, and involve reproductive failure.

The biogeochemical conditions leading to the production of subsurface irrigation drainage, culminating in death and deformities in wildlife, have been termed the 'Kesterson effect', and are prevalent throughout the western U.S.A. (Presser, 1994*a*). These conditions include: (1) a marine sedimentary basin that contain Cretaceous soils, which usually have relatively high concentrations of selenium and other trace elements; (2) alkaline, oxidized soils that promote the formation of water-soluble forms of trace elements; (3) a dry climate in which evaporation greatly exceeds precipitation, leading to salt build-up in soils; (4) subsurface layers of clay that impede downward movement of irrigation water and cause waterlogging of the cop root zone; and (5) subsurface drainage, by natural gradient or buried tile drainage networks, into migratory bird refuges or other wetlands.

The field studies conducted by USDOI indicate that the toxic threat of irrigation drainage to wetlands, fish, and wildlife is not restricted to Kesterson NWR, the San Joaquin Valley, or the State of California. Contamination has proven to be prevalent throughout the western United States (Fig. 1). Waterfowl populations are threatened in the Central and Pacific flyways, which are major passageways for migratory birds between Canada, the U.S.A. and Mexico (Presser *et al.,* 19943; Skorupa *et al., in* press). In this

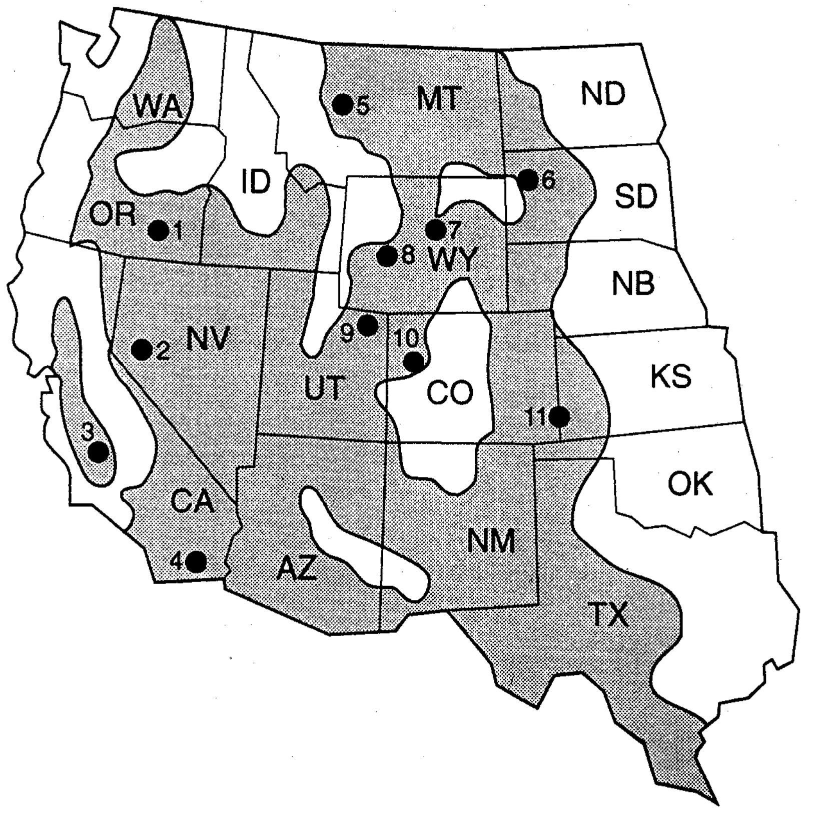

Figure 1. Arid **and semi-arid** regions of the **western** U.S.A. where irrigation is necessary to support **abundant** agricultural production (shaded areas). Dots indicate locations where, **in** addition to Resterson National Wildlife Refuge (NWR), subsurface drainage from Federal irrigation projects has caused toxicity to fish **and** wildlife (Presser *et* al., 19943). 1 = Malheur NWR; 2 = Still-water NWR; 3 = **Tulare** Lake Bed Area; 4 = **Salton** Sea Area; 5 = **Benton** Lake **NWR;** 6 = Belle Fourche Reclamation Project; 7 = **Bowdoin** NWR; 8 = **Riverton** Reclamation Project; 9 = **Ouray** NWR; 10 = Gunuison River Basin; 11 = Middle **Arkansas** River. Deformities associated with **selenium bioaccumulation in** young birds have **been found** at locations **2, 3, 5, 7, and** 9.

regard, agricultural irrigation drainage is a problem with legal implications under the Migratory Bird Treaty Act (Margolin, 1979). Authorities responsible for managing wetlands in North America and Central America must recognize irrigation drainage as a widespread problem with the potential to affect wildlife populations on an international scale.

Implications for irrigated agriculture

United States

In order to improve the conditions for wildlife at locations that have been degraded by irrigation drainage, historic freshwater inflows must be restored. However, water is a tightly regulated, Federally subsidized commodity in the western U.S.A. and almost all of the available supply is controlled by legal rights established during the past 150 years (Reisner, 1986). The water rights of agriculture have clearly been given priority over the water needs of freshwater wetlands and wildlife. Putting water back into wetlands means that less will be going to agricultural irrigation; it seems that no one wants to deal with that problem (Moore *et* al., 1990). Thus, more and more water has been squeezed out to meet contract obligations for agriculture, and wetland managers have had to get by with less, both in terms of quantity and quality (Thompson & Merritt, 1988). The 1985-92 drought in California underscored the severity of the problem and made it clear that humans are pushing nature's hydrological system to the limit.

Resolving the dilemma over water rights of agriculture and water needs of native wetlands will not be easy. The situation at Kesterson NWR was resolved after several years of scientific and political debate, at a cost of well over 100 million dollars (Harris, 1991). Kesterson was declared a toxic waste dump, taken out of the national wildlife refuge system, and partially buried. However, due to monetary, legal, and time constraints this is not a workable alternative for other wetlands already degraded by, or at risk from, irrigation drainage. Decisive actions based on current knowledge of drainwater impacts should be used to correct existing damage and prevent possible future problems. Effectively managing and restoring these wetlands will require creative thinking by wetland managers, co-operation between water authorities and natural resource agencies, and increased conservation by water users.

In California, an evaluation of methods for reducing, controlling, and managing irrigation drainage has been completed by the San Joaquin Valley Drainage Program (SJVDP, 1990). This program recommended options that included taking marginally productive agricultural lands out of cultivation, additional on-farm water conservation practices, and increased cost to water users to pay for wastewater treatment. It is likely that a combination of several measures will be necessary to improve the drainage situation. However, essentially all of the options have the potential to reduce farm income, and have received considerable opposition from agricultural interests (Harris, 1991). Recent actions by water authorities in California suggest that trade-offs are likely to be made in favor of agriculture (California State Water Resources Control Board, 1987). Water quality objectives recommended to protect wetlands were relaxed because of the projected economic impact of more restrictive regulations on farmers. The argument over agricultural economy vs. wildlife and wetlands will continue to be a central theme in the irrigation drainage issue in the U.S.A.

The evaluation of economic impacts will weigh projections of lost agricultural income against lost fish and wildlife populations, degradation of wetland habitats, diminished public recreational values, and associated reduction of revenues. Placing a dollar value on wetland uses shows that the environmental damage caused by agricultural irrigation drainage has substantial economic cost, and makes a strong argument in favor of maintaining healthy freshwater wetlands. The next few years are critical in determining the balance between agriculture and wetlands in the western U.S.A. because many of the Federal water delivery contracts that have been in place since the 1940s will be reviewed for reauthorization. Wetland managers and natural resource agencies have the opportunity to use damage assessment procedures and cost-benefit analyses to make a difference in water allocation policies. Irrigated agriculture may experience reductions in water availability along with increases in water cost.

Other countries

The possibility that irrigated agriculture could produce subsurface drainage and wildlife problems in other countries seems very likely. Several of the factors contributing to the formation of toxic drainwater in the western U.S.A. (e.g. a marine sedimentary basin containing soils with elevated concentrations of trace elements, alkaline conditions that favor the formation of water-soluble forms of trace elements, and soil salinization problems that require the use of irrigation to flush away excess salts), occur in many other arid and semi-arid regions of the world (Davies, 1980; van Schilfgaarde, 1986). It is not clear how widespread the other key element necessary for producing subsurface drainage is; i.e. the presence of layers of clay or other impermeable soil materials that impede downward movement of irrigation water. However, drainage or salinity problems have been reported from virtually every arid region where intensive irrigation occurs (Hodge & Duisberg, 1963; van Schilfgaarde, 1986), suggesting that the phenomenon may be common. Moreover, elevated concentrations of soil trace elements prone to leaching by irrigation, such as selenium and molybdenum, are known to occur in Canada, Great Britain, and Ireland (Davies, 1980).

Proposed agricultural irrigation projects should undergo a technical review to assess water demand and supply relationships, and determine the potential for drainage problems. Local geological information can be used to determine the location of impermeable subsurface soils and therefore identify areas that would become waterlogged and produce drainage. These areas should not be irrigated. Even projects that appear to be safe from drainage problems must be approved cautiously because diverting freshwater supplies away from wetlands carries great environmental risk. Preventing wildlife problems through this pre-irrigation screening process will result in less adverse impact to agriculture than explaining and correcting, at very high cost, environmental damage once it has occurred. Agricultural irrigation projects can no longer be justified on the basis of economic benefits because of the risk of environmental degradation and artificial water shortages (Livingstone & Campbell, 1992).

Environmental assessments should be made at existing irrigation projects to determine if subsurface drainage is present or could occur in the future. Finding subsurface drainage is straightforward. Lateral, subsurface flow from the margin of fields during periods of active irrigation is the best indication. However, predicting future drainage conditions is not as simple. Small increases in the application rate of irrigation water may be all that is necessary to start the production of subsurface drainage. Increased irrigation is often used to improve soil condition in areas where salinization is just begining to occur (Moore et al., 1990). Thus, as soil salinization increases, so may the potential for subsurface drainage and associated wildlife problems. Again, the use of local geological information to locate areas with impermeable subsurface soils will aid in identifying potential problem areas.

If drainage is occurring or seems likely, streams and wetlands that may be receiving the waste should be monitored for evidence of impacts. The simplest approach is to measure water quality parameters known to be influenced by irrigation drainage, i.e. levels of salinity and concentrations of trace elements such as selenium, boron, molybdenum, and arsenic. As a second step, bioaccumulative trace elements, particularly selenium, can be measured in aquatic organisms and wildlife tissues. Guidelines are available for determining what the waterborne and tissue concentrations of drainwater contaminants mean in terms of their toxic threat to fish and wildlife (Eisler, 1988, 1989, 1990; Lemly, 1993). Anticipating and evaluating potential problem areas will allow changes to be made in irrigation practices for the benefit of agriculture and wildlife.

Conclusions

Through a combination of water diversion and toxic subsurface drainage, irrigated agriculture has severely degraded wetlands and poisoned wildlife populations in the western 'United States. It is likely that similar, but as yet undetected ecological problems exist or may soon occur in other countries as well. Agricultural irrigation projects should be carefully evaluated worldwide to identify potential impacts on wildlife before effects reach the proportions of those which took place in the U.S.A.

Regaining historic freshwater supplies to wetlands is a key factor in the prevention of ecological impacts. This goal will be difficult to achieve because it requires a redistribution of water resources that can result in lost farm income. Clearly expressing the economic benefits of wildlife is necessary to successfully negotiate with water authorities. Assigning dollar values to wetland uses will substantially strengthen the argument for preserving and enhancing these important natural areas.

Water demands of agriculture have reduced freshwater inflows and negatively affected the quantity and quality of wetlands throughout the world for decades. Subsurface irrigation drainage is yet another threat to the precarious existence of many wildlife populations.

I thank J. J. Coyle and two anonymous reviewers for comments on the manuscript. The Media Production Service's Graphic Arts Lab at Virginia Tech University produced the figure. The opinions and recommendations given in this paper are those of the author and do not represent official policy of the U. S . Forest Service.

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