Chapter 11
Selenium, Salty Water, and Deformed Birds

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Abstract Selenium was identified in the 1930s as the cause of embryo mortality and severe embryo deformities when chickens were fed grains grown on seleniferous soils in South Dakota. There had been no documented occurrences of such effects in wild birds before 1983, when we studied the effects of agricultural irrigation drainage water contaminants on birds feeding and nesting at Kesterson Reservoir, located within the Kesterson National Wildlife Refuge in the San Joaquin Valley of California. The Reservoir was used for disposal of subsurface saline drainage waters from agricultural fields and was intended to provide beneficial habitat for wildlife, particularly waterfowl and other aquatic birds. Analyses of food-chain biota (plants, aquatic invertebrates, and fish) and bird tissues or eggs showed that selenium was the only chemical found at concentrations high enough to cause the observed adverse effects on bird health or reproduction. Results of the studies at Kesterson Reservoir stimulated interest and concern about the effects of selenium in agricultural drainage throughout the western USA where similar scenarios might exist (as well as in industrial settings such as mining and power generation). Those studies showed that selenium-related problems with agricultural drainage were widespread and locally significant. Problems of managing selenium in agricultural drainwater are difficult to solve or mitigate, despite intensive efforts to do so. This chapter briefly describes the field and laboratory studies that documented the effects of selenium in birds using wetlands receiving seleniferous agricultural drainage, the linkages between those studies and subsequent efforts to address the issue of selenium contamination in agricultural drainage water, and the consequent conservation gains.

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Introduction

In the 1930s, selenium was identified as the cause of embryo mortality and severe developmental abnormalities ("deformities" or "terata") in chickens (*Gallus domesticus*) that were fed grains grown on seleniferous (i.e., high-selenium) soils in South Dakota (Franke and Tully 1935). Documented occurrences of such effects in wild birds were not known until 1983, when my US Fish and Wildlife Service (USFWS) colleagues and I studied the effects of agricultural irrigation drainage water contaminants on birds feeding and nesting at Kesterson Reservoir, located in the San Joaquin Valley of California. At that time, the Reservoir consisted of a series of 12 ponds (totaling about 500 ha) within the Kesterson National Wildlife Refuge (NWR) that were used for disposal of subsurface saline drainage waters from agricultural fields. The studies initially considered various inorganic and organic chemicals that were known or suspected to occur in the wastewater. However, analyses of food-chain biota (plants, aquatic invertebrates, and fish) and bird tissues or eggs showed that selenium was the only chemical found at concentrations high enough to cause the observed adverse effects on bird health or reproduction.

The goal of this chapter is to briefly describe the field and laboratory studies that documented the effects of selenium in birds using wetlands receiving seleniferous agricultural drainage, the linkages between those studies and subsequent efforts to address the issue of selenium contamination in agricultural drainage water, and the consequent conservation gains. I also briefly describe some of my personal experiences (and the consequences) of having done studies related to selenium and agricultural drainage waters at Kesterson Reservoir where the saga began.

The references cited in this chapter and other summaries (e.g., Ohlendorf 1989, 1996, 2002, 2003; Ohlendorf and Hothem 1995; Heinz 1996; Ohlendorf and Heinz 2011) provide more details about the studies of birds mentioned in this chapter. Other studies at Kesterson Reservoir focused on fish exposed to selenium in agricultural drainage waters (see, e.g., Saiki 1986; Saiki and Lowe 1987; Saiki and Ogle 1995; Saiki and Schmitt 1985; Hamilton et al. 1990) and are not described in this chapter, because my main focus was on birds and their food-web exposures to selenium.

Background

After serving as the Assistant Director of the USFWS Patuxent Wildlife Research Center in Maryland from 1973 to 1980, I had an opportunity to open a new field research station under the Center on the campus of the University of California, Davis. During 1971 to 1973, I had conducted research on the effects of environmental contaminants on wildlife as a Wildlife Research Biologist at the Center and continued to do so as the Assistant Director. Because I was more interested in returning to life as a full-time researcher than in continuing up the administrative line within the USFWS, I voluntarily took a grade reduction and moved west. It was expected that one focus of the new field research station would be a study of the

effects of contaminants in saline agricultural drainage at the Kern NWR (located near historic Tulare Lake in the southern San Joaquin Valley of California), where plans had been made to construct experimental ponds to evaluate salinity management practices for wetlands. My plans were to add to the overall evaluation of those saline wetlands by conducting studies of the other constituents in drainwater that could affect health or reproduction of birds using the wetlands. However, the Kesterson Reservoir events (described below) arose before the plans at Kern NWR could be implemented, and those studies were never conducted.

During the 1970s and 1980s, there was much interest in the potential for using agricultural drainage water for wetland management in California's Central Valley. Most of the Valley's wetlands had been altered by flood control, drainage, or water diversion projects, and by agricultural development (Gilmer et al. 1982; USFWS 1982). Those wetlands that persisted had inadequate water supplies, and the problem was expected to worsen as more water was needed for agriculture.

In their review of published and unpublished literature, Jones and Stokes (1977) suggested it might be feasible to use irrigation drainage water to create new or restore former wetland habitats. However, they recognized the potential negative consequences for fish and wildlife resources from using low-quality water (because of high salinity and potential for pesticides and trace elements in the water) for marsh management, and the need for a comprehensive assessment. The harmful direct and indirect effects of environmental contaminants (such as pesticides and trace elements that may be leached from the soil) on fish and wildlife populations were among the significant unknowns.

Natural drainage (specifically, the downward percolation of applied irrigation water through the plant root zone) is inadequate for long-term crop production in some western portions of the San Joaquin Valley because saline water accumulates in the plant root zone (IDP 1979; Hanson 1982). To maintain productivity on those irrigated lands it is necessary to install subsurface drains to collect shallow saline groundwater (which contains salts imported with the irrigation water, but also contains selenium leached from soil) and carry it away from the fields. However, disposal of the drainage water then becomes a problem, so installation of the required subsurface drains was limited by the amount of subsurface drainage that could be discharged. To solve that problem, the US Bureau of Reclamation (Reclamation or USBR) received authorization to construct the San Luis Drain, a concrete-lined canal that was intended to carry the drainwater to the San Francisco Bay Estuary (also referred to as the Sacramento/San Joaquin Delta) for discharge (Fig. 11.1). Construction of the Drain was discontinued in 1975, however, after about 40% of it had been completed. The terminus of the Drain was at Kesterson Reservoir, which was intended to be one of the "regulating reservoirs" along the Drain where water would be stored until it could be discharged into the Estuary during high winter flows from the Sacramento and San Joaquin rivers. At Kesterson Reservoir, the water was impounded in 12 shallow ponds for evaporation but it also was intended to provide beneficial habitat for wildlife. Based on that anticipated beneficial use of the water, USFWS and Reclamation had signed a cooperative agreement in July 1970 for the management of Kesterson Reservoir and associated lands for

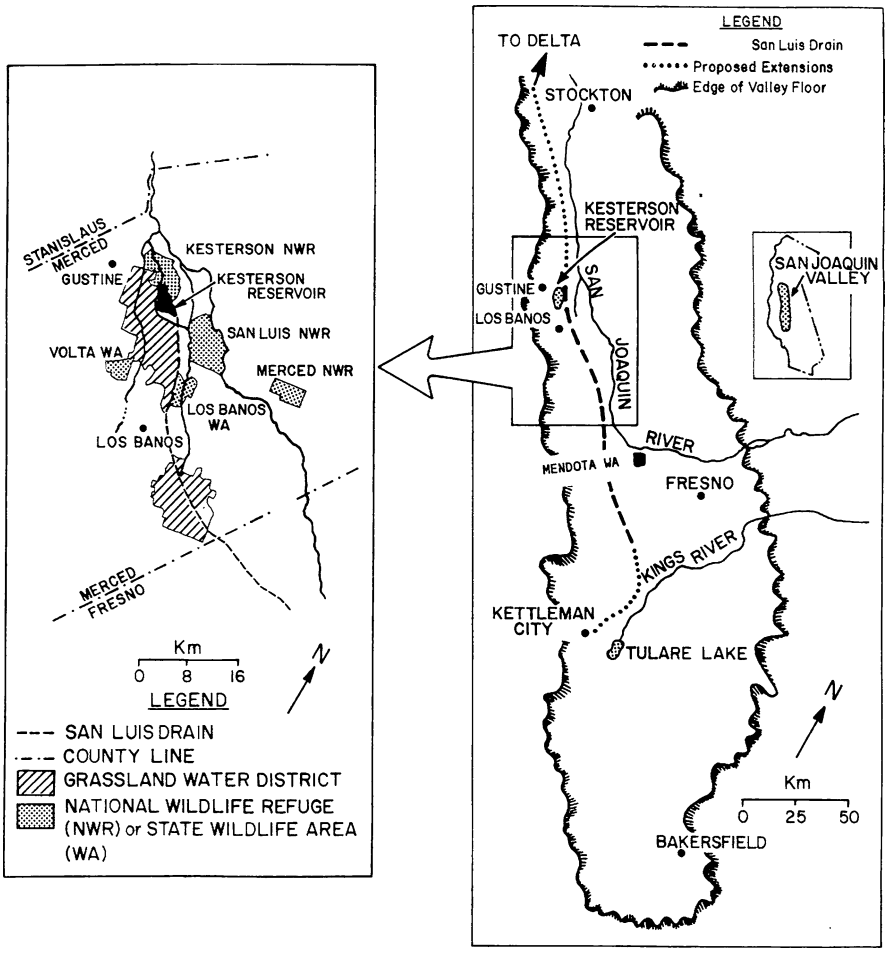

Fig. 11.1 Location of Kesterson Reservoir, Volta Wildlife Area, the Grasslands, and other features in the San Joaquin Valley, California

the conservation and management of wildlife under authority of the Fish and Wildlife Coordination Act.

The California State Water Resources Control Board (State Board) required that Reclamation complete several studies of hydrology, water quality, and potential effects on fisheries resources at the proposed discharge site) before it would approve agricultural drainwater discharge to the Estuary, but there was no requirement from the State Board for studies of wildlife using Kesterson Reservoir or the planned discharge site in the Estuary. However, the USFWS was concerned about the potential effects of chemicals in the drainwater on fish and wildlife, so the agency recommended to Reclamation that studies should be conducted at Kesterson Reservoir, the proposed discharge site, and a reference site near Kesterson that did not receive

subsurface agricultural drainwater (Volta Wildlife Area; see Fig. 11.1). Because there was no requirement from the State Board for studies of wildlife at Kesterson Reservoir or the planned discharge site, Reclamation declined to fund the proposed studies, and the USFWS undertook the studies with its own funding.

From 1971 to 1977, inflow to Kesterson Reservoir was fresh water, including a mixture of irrigation supply water and surface runoff from agricultural fields that provided high-quality wetland habitat for birds and other wildlife. Increasing proportions of the flow during 1978 to 1980 were from subsurface drains. During 1971 until about 1980, the San Luis Drain supported fish such as striped bass (*Morone saxatilis*), largemouth bass (*Micropterus salmoides*), green sunfish (*Lepomis cyanellus*), and channel catfish (*Ictalurus punctatus*). By 1982, only mosquitofish (*Gambusia affinis*) were common in the Drain and in Kesterson Reservoir, and their high abundance suggested that few predatory fish survived.

As part of our research planning effort, Mike Saiki (USFWS fishery biologist with whom I worked on the initial Kesterson study) collected a few samples of mosquitofish from the San Luis Drain, Kesterson Reservoir, and Volta Wildlife Area (the nearby reference area that did not receive subsurface agricultural drainage water). Concentrations of several metals/metalloids (arsenic, cadmium, chromium, copper, mercury, nickel, lead, and zinc) in these preliminary samples were generally similar among locations, and organochlorine concentrations were very low (Saiki 1986). Of the 23 organochlorine compounds in the analytical suite, only *p,p'*-DDE (22–44 μg/kg, wet weight [ww]) and Aroclor 1248 (60 μg/kg, ww) were detected in the mosquitofish from the Drain or Kesterson. However, there were marked differences in selenium concentrations between mosquitofish from the Drain (27–30 μg/g, ww) and Kesterson Reservoir (26–31 μg/g, ww) in comparison to those from the Volta Wildlife Area (0.39 μg/g, ww). This suggested that there were elevated levels of selenium in the Kesterson food chain for birds, and that mosquitofish are very tolerant of selenium and can accumulate high levels.

My review of the literature available at that time showed that bird embryos are very sensitive to selenium toxicity (Franke and Tully 1935; Moxon and Olson 1974; NAS 1976; Ort and Latshaw 1977, 1978). Hatchability of chicken eggs was significantly reduced when dietary selenium concentrations were 5 μg/g;[1] when dietary concentrations were between 5 and 10 μg/g, there was a high incidence of grossly deformed embryos. Typical deformities included missing eyes and beaks, edema of the head and neck, and distorted wings and feet. Because selenium in the diet of chickens at much less than 10% of the concentration found in mosquitofish from Kesterson Reservoir (converted to about 130–150 μg/g dry-weight basis to be consistent with the poultry diet) produced significant reproductive effects in chickens (described above), it seemed important to evaluate embryo mortality and deformities in a field study of aquatic birds inhabiting the Kesterson ponds.

[1] All selenium concentrations for biota in this paper are given on dry-weight basis, unless otherwise noted.

This background information provided the rationale and approach for a study to determine whether Kesterson Reservoir provided favorable habitat for aquatic wildlife, especially because of the potential for drainwater to be used elsewhere for marsh management or to be discharged into the San Francisco Bay Estuary.

The Research Phase

Research on the effects of selenium (and other contaminants) in drainwater at Kesterson began with our field study in 1983 (summarized below) that strongly implicated selenium as the chemical responsible for high rates of embryo mortality and embryo/chick deformities in wild birds that were similar to those observed previously in poultry. Following the first year of field research at Kesterson, laboratory studies were conducted at the Patuxent Wildlife Research Center and elsewhere with several species of birds that corroborated findings from the field study (see Ohlendorf 2002, 2003; Ohlendorf and Heinz 2011). Additional studies conducted at Kesterson and nearby areas in 1984 and 1985 showed the problem of selenium in agricultural drainage water was not isolated to Kesterson Reservoir.

The findings of the Kesterson studies have been reported in more detail in other publications, some of which provide illustrations of the specific embryo deformities observed in the field (e.g., Ohlendorf et al. 1986a, 1988, 1989, 1990; Hoffman et al. 1988; Hothem and Ohlendorf 1989; Ohlendorf and Skorupa 1989; Williams et al. 1989) and in several reviews that also incorporated the results of studies in other areas and those of related experimental studies (e.g., Ohlendorf 1989, 1996, 2002; Skorupa and Ohlendorf 1991; Ohlendorf et al. 1993; Ohlendorf and Hothem 1995; Heinz 1996; O'Toole and Raisbeck 1998; Ohlendorf and Heinz 2011).

The studies of selenium effects in birds have been recognized as one of the "gold standards" of retrospective ecological risk assessment, as discussed by Suter (1993). The integration/combination of related laboratory studies with the Kesterson field studies fulfilled the equivalent of Koch's postulates by recognizing a disease syndrome, identifying the causative agent, and reproducing the disease syndrome in healthy individuals by administration of the putative agent (selenium) in their diet.

Field Studies

The Beginning: Kesterson in 1983

Based on information available in 1983, my objectives in the first study at Kesterson Reservoir were to "determine whether selenium or heavy metals occur at harmful levels in aquatic birds or their food chains in the evaporation ponds at Kesterson NWR and interpret the significance of these contaminants to wildlife" (Ohlendorf 1983). This study focused on reproductive effects in aquatic birds and on

contaminants in their food chains at Kesterson Reservoir and the Volta Wildlife Area reference site (Fig. 11.1).

Methods and Study Areas

We studied several species of birds that were common at one or both of the study sites, including eared grebe (*Podiceps nigricollis*), pied-billed grebe (*Podilymbus podiceps*), American coot (*Fulica americana*), mallard (*Anas platyrhynchos*), gadwall (*A. strepera*), cinnamon teal (*A. cyanoptera*), American avocet (*Recurvirostra americana*), black-necked stilt (*Himantopus mexicanus*), and killdeer (*Charadrius vociferus*). We collected adult birds of several species at each site in spring and early summer to determine which foods they were eating and what concentrations of selenium were in their tissues at the beginning and end of the nesting season. In addition, we sampled juveniles of some of these species before fledging to determine concentrations of chemicals in their tissues, because their exposure (as nonflying young) could be more clearly associated with the area in which they were collected.

We evaluated nesting success of these species by searching for nests in favorable nesting habitats at Kesterson and Volta, marking the nests, and monitoring them (usually weekly) to determine their fate. We collected randomly selected eggs from some of the monitored nests and we collected nonrandom eggs from other nests (such as those that had failed to hatch, or sibling eggs from nests where chicks with deformities were found) for analysis. Searching for, marking, and monitoring the nests of the study species was a major effort; however, I believed the effort was warranted because impaired reproduction was likely to be a significant effect of the birds' exposure to selenium and the effects could be determined best by monitoring nests. It is unlikely that we would have understood the significance of the effects of selenium on bird reproduction without using this study approach, though some had suggested during the planning phase that it would be sufficient to do brood counts and compare "productivity" between the two study sites.

In a parallel study, Mike Saiki sampled mosquitofish, aquatic invertebrates, and plants of the types eaten by the aquatic birds (Saiki and Lowe 1987). The food-chain sampling included spatial and seasonal comparisons to evaluate changes related to inflows of agricultural drainwater to Kesterson and its evaporation during the summer.

Results and Discussion

Eared grebes, coots, ducks, stilts, and avocets nested at Kesterson in sufficient numbers for us to monitor 347 nests to late stages of incubation or hatching and thereby evaluate reproductive success (Ohlendorf et al. 1986a). Forty percent of those nests had one or more dead embryos, and 20% had at least one embryo or chick with

Fig. 11.2 Newly hatched American coot chicks in a nest at Kesterson Reservoir in 1983. Three of the chicks are normal but the one in the foreground has no eyes (note absence of blue coloration where eyes are missing). Other eggs in the nest failed to hatch, and the one that was analyzed had 44 μg Se/g (about 20 times the normal concentration). Photo by author

severe deformities (Figs. 11.2–11.4). Some chicks that hatched were blind, had no lower beak, or had no feet. In contrast, observations at Volta and findings in studies with these species elsewhere showed that the incidences of embryo mortality or deformities at Kesterson were much higher than expected. The deformities in embryos and chicks were similar to those previously found in chickens, and almost all of them were severe enough to be fatal. The deformities were often multiple, including (roughly in decreasing order of frequency) missing or abnormal eyes (anophthalmia and microphthalmia), beaks (missing, reduced, or crossed), legs and wings (micromelia and amelia), feet (ectrodactyly and clubfoot), and brain (hydrocephaly and exencephaly), and were typically bilateral.

Selenium concentrations in livers of adult and juvenile birds from Kesterson were about ten times those found at the Volta reference site (Ohlendorf et al. 1986a, 1990), and selenium concentrations in bird eggs at Kesterson usually averaged at least 20 times higher than at Volta (Ohlendorf and Hothem 1995). Mean selenium concentrations in eggs of all species at Volta were less than 3 μg/g, which is typical of normal background (U.S. Department of the Interior [USDI] 1998), whereas

means at Kesterson ranged up to nearly 70 μg/g (the geometric mean for eared grebes; see Table 11.1).

Food-chain organisms such as those eaten by the aquatic birds we studied also contained highly elevated selenium concentrations (Ohlendorf et al. 1986a; Saiki 1986; Saiki and Lowe 1987). Leaves and seeds of some wetland plants had selenium

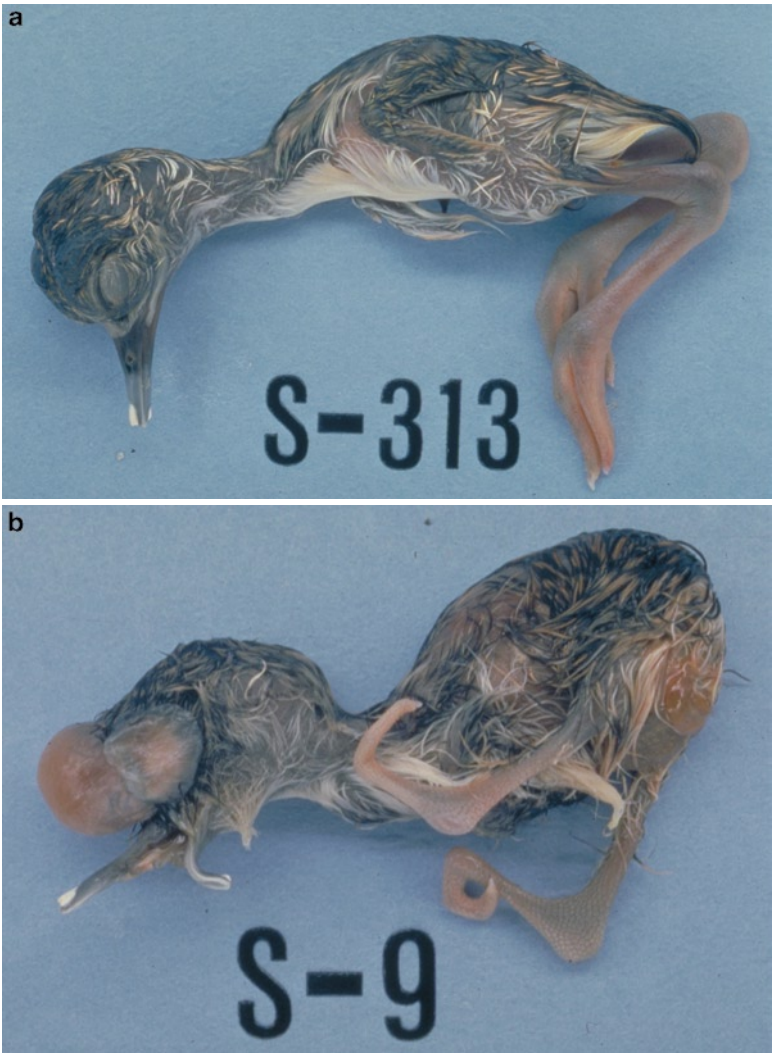

Fig. 11.3 Black-necked stilt embryos from nests at Kesterson Reservoir: (**a**) normal (S-313); (**b**) eyes missing, severe exencephaly (protrusion of brain) through orbits, lower beak curled, upper parts of legs shortened and twisted, and only one toe on each foot (S-9); (**c**) eyes missing, upper beak elongated and eroded at nostrils, lower beak missing, legs missing, and only one (small) wing (S-35). Photos courtesy of US Fish and Wildlife Service

Fig. 11.3 (continued)

Fig. 11.4 Eared grebe embryo from nest at Kesterson Reservoir showing severely deformed lower beak. Photo courtesy of US Fish and Wildlife Service

Table 11.1 Selenium Concentrations (μg/g, dry wt.) in Randomly Collected Eggs of Aquatic Birds from Kesterson Reservoir and Reference Sites, 1983–1985

			Selenium concentrations					
		Moisture[a]	Kesterson Reservoir			Reference sites[b]		
Species	Year	content (%)	*N*	Mean[c]	Min.–Max.	*N*	Mean[c]	Min.–Max.
Pied-billed grebe	1983	75.7	–	–	–	1	–	1.9
(*Podilymbus*	1984	77.1	–	–	–	2	1.70	1.6–1.8
podiceps)	1985	76.8	–	–	–	3	2.76	2.6–3.0
Eared grebe (*Podiceps nigricollis*)	1983	75.6	18	69.7	44–130	–	–	–
Mallard (*Anas*	1983	64.8	5	15.2	9.3–31	1	–	1.2
platyrhynchos)	1984	70.6	5	10.4	3.6–19	2	1.55	1.5–1.6
	1985	69.4	11	11.5	4.3–23	7	2.52	1.3–5.0
Cinnamon teal	1983	65.5	2	6.85	6.6–7.1	–	–	–
(*A. cyanoptera*)	1984	69.0	5	13.5	7.7–37	–	–	–
	1985	67.8	5	9.91	3.9–22	2	1.54	1.4–1.7
Gadwall	1983	66.2	6	18.8	9.6–32	2	0.84	0.64–1.1
(*A. strepera*)	1984	69.6	6	21.4	18–26	1	–	1.6
	1985	68.5	10	19.6	7.3–33	5	1.60	1.5–1.7
American coot	1983	73.6	17	32.4	17–74	–	–	–
(*Fulica*	1984	76.7	–	–	–	5[d]	0.756	0.59–1.1
americana)								
Killdeer	1984	74.4	9	33.1	16–50	–	–	–
(*Charadrius*	1985	72.4	21	46.4	14–180	4	2.07	1.8–2.2
vociferus)								
Black-necked stilt	1983	69.9	11	28.2	14–58	2[e]	1.61	1.3–2.0
(*Himantopus*	1984	71.5	37	24.8	5.2–64	10	2.42	1.6–3.4
mexicanus)	1985	73.4	70	35.5	4.3–100	19[f]	2.65	1.4–3.6
American avocet	1983	68.4	7	6.65	3.2–22	1	–	1.4
(*Recurvirostra*	1984	72.9	26	16.4	3.4–61	5	1.86	1.2–3.0
americana)	1985	73.6	25	32.2	3.4–88	14[g]	1.92	1.4–2.4

[a]Arithmetic mean
[b]All eggs were collected at Volta Wildlife Area; additional samples from other areas are noted below
[c]Geometric mean (GM) calculated when two or more eggs were analyzed
[d]One additional egg from Mendota Wildlife Area (0.82 μg Se/g)
[e]Ten additional eggs from Carson Lake, Nevada (GM = 1.0 μg Se/g; range = 0.44–1.7 μg Se/g)
[f]Eight additional eggs from San Francisco Bay (GM = 1.8 μg Se/g; range = 1.4–3.6 μg Se/g)
[g]One additional egg from San Francisco Bay (1.4 μg Se/g)

concentrations below 5 μg/g, but algae, rooted plants, net plankton, aquatic insects, and mosquitofish from the Kesterson ponds and the San Luis Drain typically had average selenium concentrations of 20 to more than 300 μg/g, and concentrations often were 100 times those found at Volta (Fig. 11.5). These dietary selenium

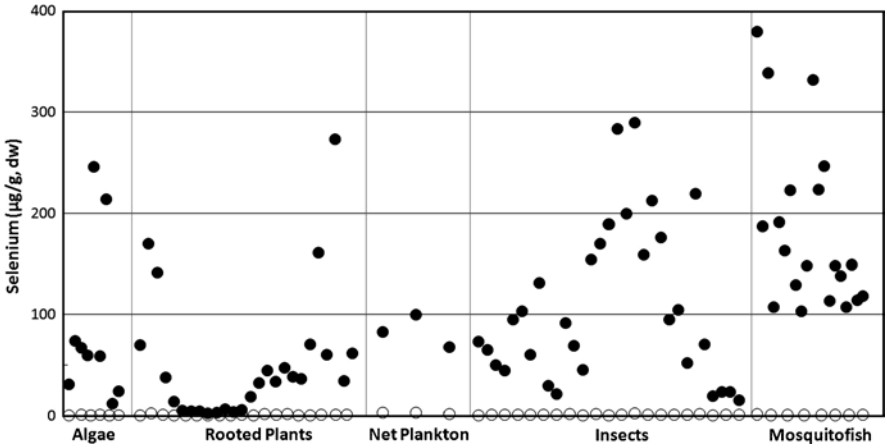

Fig. 11.5 Geometric mean selenium concentrations (µg/g, dry weight) in algae, rooted plants, net plankton, insects, and mosquitofish from Kesterson Reservoir (*filled circles*) and Volta Wildlife Area (*open circles*), 1983–1985 (data from Saiki and Lowe 1987; Hothem and Ohlendorf 1989; Schuler et al. 1990). The individual points in the figure represent values for biota at different times and locations within the two study areas.

concentrations were many times those that had caused severe reproductive impairment in earlier studies with chickens (5–10 µg/g, as summarized by Moxon and Olson 1974; NAS 1976).

The average selenium concentration in the Kesterson inflow water from the Drain was about 300 µg/L, compared to less than 2 µg/L for the Volta ponds (Presser and Ohlendorf 1987; Saiki and Lowe 1987). One of the important and unexpected observations about selenium in water and food-chain biota was that concentrations were highest in samples from the San Luis Drain and the "upstream" (i.e., near the inflow) ponds where the drainwater entered Kesterson, rather than in the "downstream" ponds (farther along the flow path within the series of ponds). (Inflow from the San Luis Drain to the upstream ponds was the only source of water to Kesterson Reservoir, so there was no dilution due to inputs of fresh water). Unlike conservative constituents present in the drainwater (such as boron and salinity) that increased in concentration through evaporative water loss along the flow path, selenium concentrations in water and biota decreased through the series of ponds (because of biological uptake and deposition to sediment), which is a pattern that has subsequently been observed in other wetland systems.

My colleagues at the Patuxent Wildlife Research Center used the results of the 1983 field study to plan a series of laboratory studies to test the effects of selenium on several species of wild birds under controlled conditions (summarized by Heinz 1996; Ohlendorf and Heinz 2011), and I used them to plan subsequent field studies at Kesterson and in the surrounding Grassland Water District (Ohlendorf et al. 1987) to increase our understanding of the nature and extent of selenium contamination issues related to agricultural drainage water in the San Joaquin Valley.

Continuing Study: Kesterson in 1984–1985

We continued to measure selenium bioaccumulation in food-chain organisms at Kesterson and Volta and to evaluate the effects of selenium on aquatic birds at the two sites in 1984 and 1985. Food-chain organisms at the two sites had selenium concentrations similar to those in 1983 (Hothem and Ohlendorf 1989; Schuler et al. 1990). Selenium concentrations in aquatic plants, invertebrates (mostly insects), and mosquitofish at Kesterson typically averaged 50 to 150 μg/g, and were far higher than the threshold dietary levels associated with impaired reproduction for poultry (Moxon and Olson 1974; NAS 1976) or mallards (as determined by studies conducted at the Patuxent Wildlife Research Center; see Ohlendorf and Heinz 2011). By comparison, food-chain organisms from Volta generally averaged 2 μg/g or less, similar to other uncontaminated areas. Bioaccumulation factors (i.e., tissue concentration [μg/g] divided by waterborne selenium concentration [μg/L]) for many food-chain organisms often were about 1,000. However, the bioaccumulation factors decreased significantly as the waterborne selenium concentrations increased, so the generalized bioaccumulation factor of 1,000 did not apply to all waterborne selenium concentrations.

Many coots were present at Kesterson during the 1984 and 1985 nesting seasons, but we found no coot nests in areas where we had found 92 nests in 1983. Unlike 1983, we found many dead coots (as well as some ducks, grebes, and other birds) at Kesterson in 1984 and 1985. We attributed this mortality and failure of coots to nest to the debilitating effects of excess selenium in the birds' diets and tissues (Ohlendorf et al. 1988, 1990; Ohlendorf 1989, 1996). The coots we collected at Kesterson, whether live or found dead, were about 25% below their normal body weights; their livers contained more selenium than in 1983, and they had lesions associated with selenium toxicosis.

In addition to high incidences of embryo mortality and abnormalities, we found poor survival of chicks that hatched for several of the aquatic bird species in 1984 and 1985 (Ohlendorf 1989; Ohlendorf et al. 1989; Williams et al. 1989). Overall, nearly 40% of the 578 nests that we could evaluate during 1983–1985 contained one or more dead or deformed embryos or chicks. Some embryo mortality was expected to occur normally, but only about 1% of the eggs from Volta contained dead embryos, and we found no abnormal embryos there. Among the young that we presumed to have hatched, there was poor survival in grebes and coots (about 2%) in 1983, and in 1984–1985 our observations indicated there was no survival among the nearly 440 avocets and stilts that apparently hatched.

Beyond Kesterson Reservoir

Grasslands of the San Joaquin Valley

In addition to continuing the study at Kesterson in 1984, we sampled birds and their eggs from the nearby Grassland Water District, which includes two areas; one is

located adjacent to Kesterson (the "North Grasslands") and the other is farther south (the "South Grasslands," nearer the source areas of the agricultural drainage water; see Fig. 11.1 and Ohlendorf et al. 1987). The water supply to the Grasslands was a mixture of subsurface agricultural drainage and other water, with an average selenium concentration in the inflow of about 50 μg/L. We found elevated selenium concentrations in several species of aquatic birds and their eggs during this study. The spatial pattern of selenium concentrations was similar to that at Kesterson; selenium concentrations were higher in the South Grasslands, near the inflow areas, than downstream in the North Grasslands. As a result of our findings, the water supply to the Grasslands was changed to exclude use of irrigation drainage water during the autumn of 1985.

Following this initial study Roger Hothem led a 2-year study of reproductive success of ducks and shorebirds nesting in the Grasslands and contaminant concentrations in their eggs during 1986 and 1987 (Hothem and Welsh 1994). Selenium concentrations were higher in eggs from the Grasslands than at an uncontaminated reference site, and concentrations in some species and locations exceeded reproductive effect levels. Nevertheless, no effects on reproduction were found in any of the ducks or shorebirds nesting in the Grasslands in 1986 or 1987, probably because of the small sample size from the more contaminated areas.

In parallel studies, birds also were sampled throughout the Grasslands for tissue analysis in 1985–1988 (Paveglio et al. 1992) and in 1989 and 1994 (Paveglio et al. 1997) to further define the spatial and species-specific patterns of contamination and to determine improvements resulting from the change to a freshwater supply for the Grasslands in 1985. Not surprisingly, these studies showed that the South Grasslands continued to be more contaminated than the North Grasslands. In addition, the livers of birds collected during the breeding and wintering periods contained selenium at concentrations associated with reproductive impairment. Selenium contamination (as measured in bird livers) had been reduced as a result of the change in water source for the Grasslands, but concentrations still were higher than background, and sometimes exceeded those associated with adverse effects.

Elsewhere in the Western USA

Following our discoveries of irrigation drainage-related contamination impacts at Kesterson Reservoir, the USDI initiated the National Irrigation Water Quality Program (NIWQP) in late 1985 to study the effects of irrigation drainage on water resources and on fish and wildlife elsewhere (Deason 1986; Engberg et al. 1998; Seiler et al. 1999; NIWQP 2009). During Phase 1, the NIWQP screened existing data from about 600 irrigation project areas and national and state wildlife refuges, primarily in the western USA, to identify other areas where agricultural drainage might be causing contamination problems. Based on the initial screening step (which was completed in 1989), the NIWQP identified 26 areas for investigation. During Phase 2, reconnaissance-level sampling at those 26 sites confirmed that harmful effects either had occurred or were likely to occur at eight of those areas (in

California, California/Oregon [along the border], Colorado, Nevada, New Mexico, Utah, and Wyoming), so more detailed studies were conducted in those areas in Phase 3. Bird embryos with multiple severe deformities similar to those in birds from Kesterson Reservoir were found in 4 of the 26 NIWQP areas (in California, Colorado, Utah, and Wyoming; see Seiler et al. 1999 for summary). Although waterborne selenium concentrations in those areas were greatly elevated (sometimes greater than 100 μg/L), they were lower than the average inflow concentrations to Kesterson Reservoir (about 300 μg/L, as described above).

Results of these investigations were published in a series of US Geological Survey (USGS) reports for the individual study areas, and they were analyzed and synthesized as the overall results for the NIWQP. The synthesis reports, such as the one by Seiler et al. (1999), also identified areas that are susceptible to irrigation-induced selenium contamination of water and biota, based on a combination of several environmental factors (such as rainfall, geology, etc.).

Laboratory Studies

As a result of our findings at Kesterson Reservoir, biologists at the Patuxent Wildlife Research Center conducted a series of laboratory studies to determine whether the effects observed in the field were related to the levels of selenium in the birds' diets (as measured by analysis of typical food items eaten by the birds at the Reservoir), and to evaluate possible interactions of selenium with other contaminants (arsenic, boron, and mercury; Stanley et al. 1994, 1996; Heinz and Hoffman 1998) that were found in drainwater at Kesterson or other sites. Most of those studies were conducted with mallards (e.g., Heinz 1993a, b; Heinz and Fitzgerald 1993a, b; Heinz et al. 1987, 1988, 1989, 1990; Hoffman and Heinz 1988, 1998; Hoffman et al. 1989, 1991; Albers et al. 1996) but studies also were conducted with birds of other species (such as black-crowned night-herons [*Nycticorax nycticorax*], Smith et al. 1988; and eastern screech-owls [*Megascops asio*], Wiemeyer and Hoffman 1996). Experimental studies also have been conducted elsewhere with mallards (e.g., O'Toole and Raisbeck 1997) and other species (such as American kestrels [*Falco sparverius*]; Yamamoto et al. 1998; Santolo et al. 1999; Yamamoto and Santolo 2000). Although these various experimental studies are mentioned only briefly here, they were closely integrated with the field studies, and they were very important in validating the field-based observations. The results from the experimental studies support the conclusion that chronic dietary selenium exposure such as that observed at Kesterson Reservoir causes severe effects on health, survival, and reproduction of birds under realistic field conditions.

Taken together, these studies support the conclusion that the health and reproductive effects observed in the field – including mortality and abnormal development of embryos and chicks and the weight loss and mortality of adults – could be attributed to the toxicity of selenium. The various studies clearly showed that a combination of observed effects (such as characteristic multiple deformities of

embryos/chicks, pathological tissue changes of the integument [including feather loss] and liver, or death) and tissue analyses (especially of food, eggs, and livers) can be used to diagnose selenium toxicosis in birds. Results of many of the laboratory studies published through 2008 were described in other reviews (e.g., Heinz 1996; Ohlendorf 1996, 2003; O'Toole and Raisbeck 1998; Ohlendorf and Heinz 2011), and they are not reiterated here.

Management/Regulatory and Public Response

Kesterson Reservoir

From the beginning, regional USFWS resource and national wildlife refuge managers were very interested in our field study at Kesterson. Soon after we began to find apparent effects in our nest monitoring, Felix Smith, a senior biologist at the USFWS office in Sacramento, California, accompanied me on one of our weekly monitoring trips on June 7, 1983. He had recently been assigned the responsibility of looking into the emerging issues involving agricultural drainage and wastewater. He has said that the experience of holding a coot egg as the chick was in the process of hatching, although it had no eyes, lower beak, or feet, greatly affected his life (Smith 2007). Thereafter, events unfolded quickly to progressively notify the agencies with either responsibility for conditions at Kesterson or for regulation of water quality in the San Joaquin Valley.

On July 8, 1983, the USFWS Field Supervisor in Sacramento sent the Regional Director of Reclamation (also in Sacramento) and other offices within USFWS a "Concern Alert" to advise them of USFWS's concern about the high incidence of embryo deformities observed in our ongoing field study. The "Concern Alert" stressed the need for additional information and outlined a course of action to begin the collection of that information. It also suggested that Reclamation and USFWS meet to discuss the work and answer any questions Reclamation may have about the study.

I had been informing my research supervisor at the Patuxent Wildlife Research Center of the unfolding events from the field study, and on July 13, 1983, I forwarded the "Concern Alert" along with a transmittal memo in which I noted "There is likely to be a lot of activity related to drain-water problems in the future." What an accurate prediction that turned out to be!

Throughout the summer I participated in meetings and briefings to provide USFWS managers with updates on the results of the field study and to accompany the USFWS managers in meetings with Reclamation as related to the study findings as they emerged. Reclamation was generally not convinced that selenium contamination of the drainage water being discharged to Kesterson was a significant issue or that it should affect plans for discharge of subsurface agricultural drainwater to the San Francisco Bay Estuary. Within the USDI, this series of meetings

culminated in a briefing for the USDI Regional Environmental Coordinator on September 12, 1983.

Then, on September 15, 1983, USFWS convened a meeting in Sacramento to advise agencies outside USDI of the preliminary study results. More than 40 individuals attended the meeting, representing Reclamation, USFWS, USGS, National Marine Fisheries Service, the State Board, Central Valley and San Francisco Bay Regional Water Quality Control Boards, California Department of Fish and Game, and California Department of Water Resources. Mike Saiki and I presented the results that were available at that time and various courses of action were discussed. Efforts of the USFWS to get a news release issued about the study findings by the time of this meeting were stalled by individuals high up in the USDI, so there was no public release of information until someone (later identified as Felix Smith) leaked some information to the media.

A barrage of news media coverage of the findings from Kesterson began when the preliminary results of this study were reported in an article in the Fresno Bee on September 21, 1983 (Blum 1983). Many other newspaper articles (though not always accurate), radio and television reports, and documentaries appeared during the next several years. I believe the research findings received so much public attention because (1) photographs of the embryo deformities provided dramatic evidence of a problem, (2) there was a plan for the agricultural drainage to be discharged to the San Francisco Bay Estuary (for which there was much public interest), and (3) the Reservoir was part of the Kesterson NWR, so many people were shocked to learn about the nature and magnitude of effects that we had observed. The NWR was supposed to provide high-quality wetland habitat for wildlife, but the contaminated water caused severe impacts on the wildlife it was supposed to benefit. The photographs of embryos with deformities clearly showed that something was wrong at Kesterson, and the images quickly circulated through the regional and network news media. Some who had opposed completion of the San Luis Drain to discharge agricultural drainage to the Estuary for other reasons used the findings of the Kesterson studies to fight that controversial project. In addition, there were substantial disagreements among involved federal agencies as to the significance of the findings (see review by Garone 1999).

Following the initial release of information about the Kesterson bird studies, the rest of 1983 was hectic, but resulted in significant movement in late 1983 and 1984 toward better understanding and taking action toward solving the irrigation drainage issues (though many still remain to this day).

On October 28, 1983, US Congressman George Miller sent USFWS Director Robert Jantzen a letter asking for information about the Kesterson studies, expressing concern about the issue of contaminants in irrigation drainwater, and asking about the level of cooperation between Reclamation and USFWS on the management of Kesterson. Congressman Miller was very interested in the ongoing studies that were important to his constituents and he remained engaged in the issue over the years. Some of the results for the bird study as well as results of Mike Saiki's fish study were incorporated into the Director's reply letter dated November 29, 1983.

On December 3, 1983, University of California, Berkeley hosted a conference on "Contaminants in Agricultural Waste Water: A Problem for the S. F. Bay Region as Well as the Central Valley?" for which I was an invited speaker to talk about "What has been observed at Kesterson National Wildlife Refuge." I was able to provide information that was available at that time, and I noted a high degree of interest among the conference participants. Congressman Miller also was a speaker at this conference and spoke about "political perspectives" of the issue.

Then on December 5–7, 1983, Reclamation held a conference on "Research Issues Associated with Toxicity Problems at Kesterson Reservoir, California" to which they invited individuals familiar with selenium issues in locations such as South Dakota and those with experience in studying the effects of selenium in poultry (e.g., Dr. J. D. Latshaw). The outside experts concluded that selenium likely was causing the effects we had observed in birds at Kesterson, as was subsequently confirmed by the studies described in previous sections. In addition to supporting our preliminary assessment of the relationship between selenium and the observed effects, this conference resulted in forward movement among the federal agencies. At the conclusion of the conference, Reclamation Regional Director David Houston outlined his proposed "action plan" that included the following elements:

- Immediate action – reduce exposure of birds at Kesterson to selenium.
- Short-term action – continue data collection and reanalyze options to minimize drainage water production.
- Long-term action – establish an interagency study program, within Interior, consisting of Reclamation, USFWS, and the USGS to further define and resolve the selenium issue.

San Joaquin Valley

In August 1984, USDI Secretary William Clark and California Governor George Deukmejian established the San Joaquin Valley Drainage Program (SJVDP), with Reclamation, USFWS, USGS, California Department of Fish and Game, and California Department of Water Resources as the principal participating agencies. Over the next 6 years, the SJVDP studied the problems of subsurface agricultural drainage in the western San Joaquin Valley intensively and produced a management plan (SJVDP 1990) that recommended a combination of components to address the problem, including the following:

- Source control, mainly on-farm improvements in application of irrigation water to reduce deep percolation
- Drainage reuse, which consisted of a planned system of drainage water reuse on progressively more salt-tolerant plants
- Evaporation systems, including evaporation ponds planned for storage and evaporation of drainage water remaining after reuse on salt-tolerant plants

- Land retirement – cessation of irrigation of areas in which underlying shallow groundwater contains elevated levels of selenium and soils are difficult to drain
- Discharge to the San Joaquin River, as controlled and limited discharge of drainage water from the northern portion of the valley, while meeting water quality objectives
- Protection, restoration, and provision of substitute water supplies for fish and wildlife habitat, intended to replace drainage-contaminated water previously used for wetlands and to allow protection and restoration of contaminated fisheries and wetland habitat
- Institutional changes that included tiered pricing for irrigation water, improved scheduling of water deliveries, water transfers and marketing, and formation of regional drainage management organizations to aid in implementing other plan components

The USFWS initiated a waterfowl "hazing" program at Kesterson Reservoir in September 1984 in an attempt to minimize exposure of birds to the high-selenium environment of the ponds. Because it was important for the birds to have some other habitat to move to, USFWS requested that Reclamation help provide alternate habitat to lure the birds away from Kesterson. At about this same time, the California Department of Fish and Game and the California Department of Health Services warned that coots from Kesterson should not be eaten because of selenium contamination.

On February 5, 1985, the State Board adopted Cleanup and Abatement Order WQ 85-1 that required USDI to close, upgrade, clean up, and/or otherwise abate the nuisance from Kesterson Reservoir within 3 years. The Order further required Grassland Water District to develop a plan to control selenium concentrations in agricultural drainage water entering the District.

USDI Secretary Donald Hodel ordered the immediate closure of Kesterson Reservoir and the San Luis Drain on March 15, 1985, and termination of irrigation water deliveries to 42,000 acres of land within the Westlands Water District (WWD) where the subsurface drainage water originated. This decision by the Secretary was based on a legal analysis that determined that continued operation of the Reservoir might constitute a violation of the Migratory Bird Treaty Act.

When the decision by Secretary Hodel was announced during a public meeting in Los Banos, California, on March 15 (just 5 days after 60 minutes [the TV news program] had aired a story about Kesterson and the Drain), there was an immediate response of anger and concern from the growers attending the meeting. Because of that response and reported threats for our safety, the USDI scientists attending the meeting were abruptly evacuated to return to Sacramento. Growers were shocked about the impending loss of irrigation water and their inability to discharge subsurface drainage from their fields, which threatened their livelihood.

On April 3, 1985, USDI and WWD signed an agreement ensuring continued delivery of irrigation water by USDI to WWD, but requiring phased reductions in drainage flows by WWD through the Drain to Kesterson, with zero inflow by June 30, 1986.

Reclamation undertook several studies and control actions to reduce the hazard of selenium exposure to aquatic birds (USBR 1986; USDI 1989). In particular, Reclamation halted inflows of agricultural drainage to Kesterson in 1986 and subsequently, in 1988, de-watered the Reservoir and filled all areas to at least 15 cm above the expected seasonal (winter) elevation of high-selenium groundwater. These actions effectively transformed the Reservoir into terrestrial habitats, as described by Ohlendorf and Santolo (1994). To mitigate for the loss of wetlands at the Reservoir, Reclamation provided additional fresh water to the Grassland Water District as alternative habitat and for nuisance abatement in 1988.

Monitoring of Kesterson has been conducted since 1987 to measure selenium concentrations in representative plants and animals using the site and to determine whether adverse effects occurred (Ohlendorf and Santolo 1994; Byron et al. 2003). The data from the monitoring program during 1989 through 1991 were used to estimate likely future levels of selenium in various biota, assess risks of adverse effects to animals using the site, identify needs for contingency plans for site management, and recommend further research and monitoring to provide the information needed to improve management of the site.

The risk assessment based on the 1989–1991 data concluded that selenium concentrations in terrestrial plants and animals were not expected to change markedly in the next 20 years (Ohlendorf and Santolo 1994). No adverse effects had been documented in terrestrial birds or mammals, and no adverse effects were expected in the future.

Surface ponding of rainwater occurs in some portions of Kesterson Reservoir during very wet winters (Ohlendorf and Santolo 1994; Byron et al. 2003). Ephemeral pools that form under current conditions, and those expected to occur in the future, result from the accumulation of rainwater, rather than from rising groundwater. Although these pools are formed by rainwater, selenium concentrations in the pools averaged less than 10 μg/L, but concentrations up to 162 μg/L were measured in some pools. These concentrations and those in aquatic invertebrates collected from them were high enough to be of concern for aquatic birds (such as waterfowl and shorebirds). The greatest concern was that these pools may form during late winter or spring and persist during the nesting season of aquatic birds, which might feed on aquatic plants and invertebrates in the pools if they persisted long enough to support these food-chain components.

As a result of the ecological risk assessment described by Ohlendorf and Santolo (1994), the monitoring program was revised in 1995 to be less costly (e.g., sampling fewer kinds of biota, and sampling every 3 years) but still sufficient to determine whether the model predictions (described above) were correct. In addition, further studies with terrestrial birds such as the American kestrel (e.g., Yamamoto et al. 1998; Santolo et al. 1999; Yamamoto and Santolo 2000) were conducted during subsequent years to resolve some of the unknowns identified by the risk assessment.

This new information, along with monitoring results since 1989, was evaluated in a subsequent ecological risk assessment that focused on the terrestrial and aquatic wildlife using the site (CH2M HILL and LBNL 2000; Byron et al. 2003). The overall conclusions of the risk assessment were that future soluble

(i.e., bioavailable) soil selenium levels will be similar to those observed over the past decade, waterborne selenium concentrations in rainwater pools can be predicted on the basis of soil selenium where the pools form, and selenium concentrations in terrestrial and rainwater-pool biota will continue to be elevated above normal background-site levels, but there is low risk to wildlife for several reasons. A model developed using the historic (127-year) Kesterson-area rainfall data and observed ponding on the site since 1989 (including winter of 1997–1998, the year of maximum rainfall) indicated that there is low probability that substantial portions of the site would be flooded during the spring breeding season for birds, so their exposure during that critical period would be minimal. Selenium concentrations in terrestrial birds and mammals also will be greater than normal background, but they are expected to be below levels known to cause health or reproductive effects. As a result of the findings from this risk assessment, the frequency of monitoring was further reduced to a 5-year frequency for 2001, 2006, and 2011. Thereafter, if conditions were stable, long-term management but no further monitoring would be recommended.

Following the closure of Kesterson Reservoir as a disposal site for subsurface agricultural drainage, growers were required to find on-farm ways of managing salinity-affected lands and any associated subsurface drainage water that was collected from the lands. Examples include increasing the efficiency of irrigation (thereby generating less drainage water for disposal), re-cycling/blending the drainage water with fresh water and using it for irrigation, and growing more salt-tolerant crops.

In other portions of the San Joaquin Valley (outside of Kesterson) and the western USA, management actions have been taken as a result of the SJVDP and NIWQP, as described above. However, management of selenium in agricultural drainwater remains a difficult problem. In the northern San Joaquin Valley, dischargers formed the San Luis & Delta-Mendota Water Authority in 1992. This is an administrative body consisting of several water agencies representing about 2,100,000 acres supplied with water by 29 federal and exchange water service contractors. The Authority oversees use of the San Luis Drain and administers conveyance of agricultural drainwater from several irrigation/drainage districts through adjacent wildlife management areas to Mud Slough, a tributary of the San Joaquin River. This activity is identified as the Grassland Bypass Project, and it has demonstrated success in lowering the concentrations of selenium being discharged to the river. Their current Use Agreement for the San Luis Drain for this project expired at the end of 2009, so they prepared an Environmental Impact Statement/Environmental Impact Report (Entrix 2008) to support receiving a new Use Agreement that would allow the Grassland Bypass Project to continue through 2019. Discharges to the San Joaquin River are regulated under a Total Maximum Daily Load (TMDL) allocation (CVRWQCB 2001).

In the southern San Joaquin Valley, options for disposal of subsurface drainwater are limited, because the water must be managed within the Valley (i.e., no discharge to the river). In the 1980s there were more than 20 groups of evaporation pond basins situated in the southern portion of the Valley, but several of those systems were closed by 1995 so that the total area of evaporation ponds was reduced from more than 7,000 acres to an area of less than 5,000 acres (EPTC 1999). The remaining ponds are regulated by the State of California through Waste Discharge Requirements (WDRs) that

include mitigation measures for pond design and operation such as minimum water depth of 2 ft, steepening of side-slopes to 3:1, vegetation control, removal of windbreaks/islands, disease surveillance and control program, invertebrate sampling, and hazing to reduce bird use and the impacts of selenium in the ponds on birds.

In addition to the mitigation measures described above, the USFWS developed protocols for two mitigation approaches for unavoidable impacts by providing foraging habitats for targeted waterbirds so that selenium exposure of birds could be reduced (Skorupa and Schwarzbach 1995a, b). They included development of compensation habitat (distant from the evaporation ponds being mitigated) and creation of alternative wetland habitats (near the evaporation ponds, to "dilute" the exposure of birds using the ponds). Based upon preliminary estimates of unavoidable losses and required compensation and/or alternative habitats, WDRs were adopted for several evaporation basin systems (EPTC 1999). Monitoring of bird use and selenium concentrations in eggs demonstrated that one of the large compensation habitats was very attractive to shorebirds (Davis et al. 2008) and that alternative freshwater habitat adjacent to an evaporation pond resulted in lower selenium exposure of shorebirds (Gordus 1999).

Reclamation has completed an Environmental Impact Statement (USBR 2006) and a Record of Decision (USBR 2007) for agricultural drainage from the San Luis Unit (which was the source of the drainage that was discharged to Kesterson Reservoir) and from lands immediately adjacent to the Unit (total drainage study area of about 379,000 acres). They describe the drainage problem and the limited potential solutions for the area, and they recommend an approach for management of seleniferous drainwater. Briefly, Reclamation developed and evaluated alternatives to meet the following four objectives:

- Drainage service will consist of measures and facilities to provide a complete drainage solution, from production through disposal, and avoid a partial solution or a solution with undefined components.
- Drainage service must be technically proven and cost effective.
- Drainage service must be provided in a timely manner.
- Drainage service should minimize adverse environmental effects and risks.

After considering several alternatives, Reclamation selected an alternative for implementation (called "In-Valley/Water Needs Land Retirement Alternative"). Due to the expected costs for implementation of that alternative, it was considered likely that new authorizing legislation would be needed to increase the appropriations ceiling beyond what was authorized by the San Luis Act of 1960 (USBR 2007).

The selected alternative (like all the Action alternatives) includes on-farm/in-district actions to reduce drainwater through irrigation system improvements, seepage reduction, shallow groundwater management, and drainwater recycling; drainage collection systems; and regional reuse facilities (USBR 2007). In addition, the selected alternative would treat drainwater from the regional reuse facilities with reverse osmosis and biological selenium treatment before containment in evaporation basins (which would total about 1,900 acres). Reverse osmosis would reduce the drainwater volume by half and produce an equivalent amount of clean product water. The alternative also would target retirement of lands with selenium concentrations

in the shallow groundwater above 20 μg/L (about 194,000 acres). This alternative was formulated to retire sufficient land to balance water needs with the lands remaining in production in the Unit.[2]

Presser and Schwarzbach (2008) evaluated constraints on drainage management and the implications of various approaches to management that included the San Luis Drainage Feature Re-evaluation (USBR 2006, 2007), approaches recommended by the SJVDP (1990), other recent conceptual plans, and other USGS models and analyses relevant to the western San Joaquin Valley. They concluded that rather than a lack of information, there is a lack of decision analysis tools to enable meeting the combined needs of sustaining agriculture, providing drainage service, and minimizing impacts to the environment. A more formal decision-making process may better address uncertainties inherent in the analyses, help optimize combinations of specific drainage management strategies, and document underlying data analysis for future use. Among the benefits of such a process of decision analysis are that it provides the flexibility to move forward in the face of uncertainty. They noted, however, that it requires long-term collaboration among stakeholders and a commitment to formalized adaptive management.

All of the proposed management strategies seek to reduce the amount of drainage water produced (Presser and Schwarzbach 2008). Land retirement also is a key strategy to reduce drainage, because it can effectively reduce drainage to zero if all drainage-impaired land is retired. Within the proposed area of drainage there are, for all practical purposes, unlimited reservoirs of salt (imported with irrigation water) and selenium stored within the aquifers and in Valley soils that were formed from the Coast Ranges on the west side of the Valley. A selenium mass balance analysis by USGS quantified the approximate amount of selenium exposed on the landscape and contained in each waste-stream component for the land retirement alternatives in the San Luis Drainage Feature Re-evaluation Environmental Impact Statement. A third of the selenium in drainage water is expected to be lost in the first step of the agricultural water reuse areas and selenium bio-treatment, if successful, is expected to reduce the selenium concentration to 10 μg/L in water to be evaporated. Elsewhere in the western USA, remediation planning was conducted for five sites identified as posing risks for

[2]Costs of the selected alternative were evaluated by Reclamation in a Feasibility Report (USBR 2008) that considered technical feasibility and environmental feasibility along with economic and financial feasibility. The selected alternative was found to be technically and environmentally feasible. However, the economic feasibility evaluation found that the selected alternative could not be justified in comparison to the no-action alternative (i.e., it would not provide a positive net benefit). The financial feasibility examined and evaluated the project beneficiaries' ability to repay the Federal Government's investment in the project over a period of time consistent with applicable law. The remaining authorized construction cost ceiling for the San Luis Unit was about $428.7 million, whereas the estimated cost of the selected alternative was $2.69 billion. None of the beneficiaries would be able to repay their share of the project cost if the selected alternative were implemented. The resulting recommendation of the Feasibility Report was to implement the selected alternative, contingent on several required Congressional actions to increase the construction cost ceiling and take associated actions to implement the drainage solution.

wildlife due to selenium in California, Colorado, Nevada, Utah, and Wyoming during Phase 4 of the NIWQP (NIWQP 2009). Planning was coordinated with appropriate Federal, State, and local agencies. The planning process was led by the bureau (Reclamation or Bureau of Indian Affairs) responsible for the irrigation project and governed by a core team made up of representatives from Reclamation or Bureau of Indian Affairs (as appropriate), USGS, and the USFWS. A technical team worked under the direction of the core team to evaluate various technical issues related to the proposed remediation alternatives.

Phase 5 of the NIWQP was implementation of corrective actions identified in Phase 4 (NIWQP 2009). Two projects, or wetland sites within project areas, were in Phase 5 remediation in 2005 (Gunnison/Grand Valley, Colorado; Middle Green River, Utah). The core team for the Gunnison/Grand Valley Project determined that there were over 20 wetland sites that could require remediation. Orchard Mesa Wildlife Area and Colorado River Wildlife Area were remediated by 2005 in the Grand Valley. In the Gunnison area, a lateral piping project in cooperation with the Uncompahgre Valley Water Users Association was initiated and was still in process as of 2005, when further funding for NIWQP ended. The Gunnison/Grand Valley Core Team was also working in cooperation with the Gunnison Basin and Grand Valley Selenium Task Forces.

In 2005, remediation activities in the Middle Green River Project in Utah included extending drains away from Stewart Lake Waterfowl Management Area to the Green River and construction of the seepage collection system in Stewart Lake (NIWQP 2009). Another important source of selenium to Stewart Lake (in addition to irrigation drainage) was seepage from a sewage-lagoon system constructed for the city of Vernal, Utah upgradient from the lake (USGS 2003). This system of lagoons did not directly discharge treated wastewater to Ashley Creek (a tributary of Stewart Lake), but it was constructed on Mancos Shale and seepage from the lagoons mobilized selenium from the fractured shale and discharged it to Ashley Creek in seeps and shallow groundwater. Because of the contamination resulting from lagoon seepage, a new wastewater treatment facility was constructed for Vernal, and the sewage lagoons were decommissioned. The facility was operational in April 2001, and releases of selenium to Ashley Creek declined.

Conservation Gains

Estimates of the numbers of aquatic birds that died in other areas are not available, but I estimated that more than 1,000 birds died due to selenium toxicity at Kesterson Reservoir in 1983–1985 (Ohlendorf 1986a; U.S. General Accounting Office [USGAO] 1987). Discovery of the effects of selenium on birds (and fish) at Kesterson Reservoir, and subsequently at other sites in the western USA where seleniferous agricultural waters were entering wetland habitats, created an awareness of the needs for resource protection (Engberg et al. 1998). Based on experience from the SJVDP and NIWQP, it became evident that the success of selenium management

plans depends on partnership between federal, state, and local entities and on strong commitments by all participants to the management efforts.

It is not possible to quantify the area of aquatic or wetland habitats that directly benefitted from the awareness that selenium is a chemical of concern in agricultural drainage in certain parts of the western USA, but the total is almost certainly in the hundreds of thousands of acres. Water management has changed in the agricultural landscape, and there is much more regulatory control to minimize the exposure of aquatic birds to harmful levels of selenium, as noted in the previous section.

Realization that there was a problem with the intended disposal of agricultural drainwater to the San Francisco Bay Estuary derailed the plans for that discharge, and construction of the Drain was never completed. Thus, Kesterson Reservoir was not expanded to the anticipated 5,900 acres, other regulating reservoirs for the temporary storage of San Joaquin Valley drainage along the route of the Drain were not built, and discharge to the Estuary occurs only through regulated discharges via the San Joaquin River (the Grassland Bypass Project mentioned above). Concurrent with our studies at Kesterson, we also found elevated selenium concentrations in San Francisco Bay (Ohlendorf et al. 1986b, White et al. 1987), so increased discharges to the Estuary would have exacerbated the problem (Presser and Luoma 2006).

The results of our studies at Kesterson, in combination with other emerging knowledge about occurrence of selenium in the environment, stimulated research in a number of other exposure scenarios. Field and laboratory selenium research as related to aquatic habitats (especially concerning fish and birds) expanded rapidly in the 1980s and 1990s. As a result, selenium was found to be an issue of concern with regard to mining of coal, phosphate, and metals; disposal of fly ash from coal-fired power plants; and refining of petroleum (see Frankenberger and Engberg 1998; Chapman et al. 2010). Effects of selenium on fish have been documented in many of the same areas where selenium is of concern for birds.

Human Element

My personal experience in studying the effects of selenium on birds at Kesterson Reservoir was a mixture of excitement in making a significant scientific discovery, distress in seeing the devastating effects selenium was causing in bird embryos and hatchlings, a flurry of activities caused by media coverage of the study, and an introduction to the politics of water management in the West. I had anticipated there would be effects on egg hatchability and embryo development, but actually seeing the effects – especially the severely deformed embryos and hatchlings – was disturbing. In most settings, I was able to describe my findings in a matter-of-fact scientific manner, but there were occasions when my self-control broke down, and it was difficult to discuss the results of the study. In those cases, I had to slow down, take a deep breath, and regain my composure before continuing.

I had not anticipated the level of media coverage that would focus on the study as soon as the preliminary results were made public. By nature, I was inclined to

focus on quietly and competently doing my work and to publish my findings in the normal course of completing the research and publication process. However, that was not to be. There were frequent requests for interviews from the news media (especially newspapers and television, but also on National Public Radio), and they borrowed the close-up photos of some of the deformed embryos to use in running their stories. Regulatory and resource agencies also borrowed the photos, and they have been widely circulated and printed in various publications. My choice in having those photos taken by a professional photographer was a wise decision, as they provided clear documentation of my observations.

In addition to the local and regional media, the story of Kesterson Reservoir was covered (usually accompanied by some of the photos of deformed embryos) by many conservation organizations in their publications (far too numerous to list) as well as by National Geographic magazine (Madson 1984), a public television documentary (KQED; "Down the Drain" October 10, 1984), 60 minutes (March 10, 1985), a news team from British Broadcasting Corporation (BBC Natural History Unit; Fall 1986, "Vanishing Earth"), plus an investigation by the USGAO (1987), and congressional hearings on the subject.

Initially, my research findings were viewed as a milestone in the Environmental Contaminants Research Program of the Patuxent Wildlife Research Center and the USFWS, and in the mid-1980s I received two USFWS Special Achievement Awards for outstanding performance as a research scientist. This study occurred during a period when there was lowered concern and interest about the effects of environmental contaminants on wildlife than had existed during the hearings about the banning of DDT in the early 1970s and other highly visible events, so my findings spurred interest and a number of other studies related to the effects of selenium in birds (described above).

By the late 1980s, however, I was receiving much less support from my research headquarters, and the "inconvenient" findings of my research, as well as the extensive requests for early use of the research results in making management decisions or for public disclosure, were wearing thin on research administrators' patience. I was advised that it was unlikely I would receive a promotion anytime soon that would put me back to my previous grade (which I had given up to move to California and become a full-time researcher). During one visit by an administrator I was told that I was "more trouble than I was worth." Some have said that comment was intended as a joke; it did not seem that way to me, and by 1990 I was able to find a very interesting, challenging job as an environmental consultant, where I have been happy to be making a difference while continuing my interests in the ecotoxicology of selenium.

Harris (1991) describes some of the background and fallout of the studies at Kesterson Reservoir and other parts of the San Joaquin Valley for those of us who were involved in studying the effects of selenium. I was not the only one who had a career-altering experience in the process. As Felix Smith said as we were examining the severely deformed coot chick that was hatching on June 7, 1983, (described above), "I don't think our lives will ever be the same" and he has right. In the end, it seems that short-term political expediency will prevail over scientific evidence

when there is a conflict, especially when the research findings have large implications for interests other than the environment.

In general, our discoveries of the effects of selenium on birds at Kesterson Reservoir have made a significant contribution to environmental stewardship, though there was a personal cost to several of us who were doing the research or disseminating information about the work. The awareness of selenium's potentially toxic effects have expanded to other sources, such as mining (primarily coal, metals, and phosphate), power generation (mainly associated with fly ash), and petroleum extraction or refining. Aquatic birds exposed in environments affected by agricultural irrigation or industrial activities continue to be at some risk, but many advances in selenium evaluation and management have been made over the past 25 years to reduce the levels of exposure and effects. Nevertheless, the problems remain daunting, because of the complex biogeochemistry of selenium in the environment.

In reflecting on my experiences and my career path that changed as a result of the research that I undertook at Kesterson Reservoir in 1983, a couple of logical questions might be "Is there something I would have done differently?", and "Are there critical actions (perhaps toward a particular person with a political agenda, speaking to the press, etc.) that came back to bite me in the end?"

My overall sense is that there is not much I would have done differently, though I realize there is a possibility that might be interpreted as denial of responsibility on my part for what unfolded. Throughout, I did my best to focus on the science and understanding of selenium cycling and behavior in the environment and how selenium affects animals that are exposed to it. By maintaining objectivity and not taking a political or partisan position on what should be done, I believe I was able to focus on discovery of new information that could be applied or used by others toward making management decisions and that the research findings have been broadly accepted as being well documented. When possible, I provided interpretation of the data, because selenium biogeochemistry and ecotoxicology are complex and not easily understood. I do not profess to know everything on those subjects, but I tried to stick to the facts, as I understood them. I believe that is essential if the research findings are to be accepted as being valid and unbiased.

Because of the urgency of having usable information available for making decisions as related to the management of agricultural drainage water in the San Joaquin Valley, there was a lot of pressure for us to get our samples analyzed quickly and to provide interpretation when we were reasonably confident of what the data meant. This sometimes resulted in my speaking to the press or other news media directly or in releasing photos for their use, but I followed protocols in getting clearance for doing so. When I received invitations for presentations at meetings or symposia I routed them up through my administrative line within the USFWS. Unfortunately, some of those requests apparently were viewed by some individuals in the agency as promoting an activist agenda and were denied, which sometimes resulted in extensive back-and-forth exchanges about why presentations were being denied. In the end, that came back to bite me, and it seemed that it would have been safer to focus on issues of lower public interest. Nevertheless, since leaving the USFWS 20 years ago I have

continued to focus on selenium-related issues for study, understanding, and management, and have enjoyed the opportunities to make a difference toward our stewardship of the Earth that we are borrowing from future generations.

Summary

Selenium was identified in the 1930s as the cause of embryo mortality and severe embryo deformities when chickens were fed grains grown on seleniferous soils in South Dakota. There had been no documented occurrences of such effects in wild birds before 1983, when we studied the effects of agricultural irrigation drainage water contaminants on birds feeding and nesting at Kesterson Reservoir, which was located within the Kesterson NWR and was used for disposal of subsurface saline drainage waters from agricultural fields. The Reservoir was intended to provide beneficial habitat for wildlife, particularly waterfowl and other aquatic birds.

During 1983–1985, we studied the exposure and effects of contaminants on several species of birds that were common at one or both of our study sites (Kesterson Reservoir and a nearby reference site). Analyses of food-chain biota (plants, aquatic invertebrates, and fish) and bird tissues or eggs showed that selenium was the only chemical found at concentrations high enough to cause the adverse effects on bird health or reproduction we observed.

Results of the studies at Kesterson Reservoir stimulated interest and concern about the effects of selenium in agricultural drainage in other portions of the San Joaquin Valley of California and the western USA where similar scenarios might exist. Those studies showed that selenium-related problems with agricultural drainage were widespread and locally significant. In addition, selenium was found to be an issue of concern with regard to mining of coal, phosphate, and metals; disposal of fly ash from coal-fired power plants; and refining of petroleum. Effects of selenium on fish have been documented in many of the same areas where selenium is of concern for birds.

Management problems of selenium in agricultural drainwater are difficult to solve or mitigate, despite intensive efforts to do so. There is no single action that can be implemented to manage seleniferous drainage; instead, a combination of actions (such as source control, drainage reuse, evaporation systems [designed to minimize bird use], land retirement, controlled discharges, etc.) must be used.

Discovery of the effects of selenium on birds (and fish) at Kesterson Reservoir, and subsequently at other sites in the western USA where seleniferous agricultural waters were entering wetland habitats, created an awareness of the needs for resource protection. Based on experience from the SJVDP and NIWQP, it became evident that the success of selenium management plans depends on partnership between federal, state, and local entities and on strong commitments by all participants to the management efforts. There has been success in some areas, but management of agricultural drainage is still a significant problem in many others.

Our discoveries of the effects of selenium on birds at Kesterson Reservoir also have made a significant contribution to environmental stewardship though the

awareness of selenium's potentially toxic effects through industrial activities such as mining (primarily coal, metals, and phosphate), power generation (mainly associated with fly ash), and petroleum extraction or refining. Aquatic birds exposed in environments affected by agricultural irrigation or industrial activities continue to be at some risk, but many advances in selenium evaluation and management have been made over the past 25 years to reduce the levels of exposure and effects. Nevertheless, the problems remain daunting, because of the complex biogeochemistry of selenium in the environment.

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