AN ABSTRACT OF THE THESIS OF

Carol A. Schuler for the degree of Master of Science in Fisheries and Wildlife presented on April 15, 1987.

Title: Impacts of Agricultural Drainwater and Contaminants on Wetlands at Kesterson Reservoir, California

Abstract Approved: Redacted for Privacy

Robert G. Anthony

Kesterson Reservoir (Kesterson) received subsurface agricultural drainwater containing high levels of salts and other minerals from farmland in the San Joaquin Valley of California. Aquatic plants and invertebrates were sampled at Kesterson in May, August, and December of 1984. The reservoir supported a different biota and lower species diversity than a nearby control site (Volta WMA). Kesterson had a greater plant and seed biomass while Volta had a greater invertebrate abundance. Submergent habitat at Kesterson was dominated by widgeongrass (*Ruppia maritima*) while Volta was dominated by horned pondweed (*Zannichellia palustris*). Several aquatic invertebrates, including Amphipoda, *Eylais*, Gastropoda, *Neomysis*, Hirundinea, and Belostomatidae were common at Volta but were never observed at Kesterson.

Kesterson supported a greater abundance of diatoms (*Nitzschia*), Oligochaeta, Ephydridae, Stratiomyidae, Tabanidae, and Syrphidae while these were rarely encountered at Volta. Community structure at Kesterson was most likely influenced by high concentrations of salts, nitrogen, boron, and possibly selenium.

Bioaccumulation of selenium and other trace elements in wetlands and waterfowl foods at Kesterson was investigated during May, August, and December of 1984. High concentrations of selenium were found in water, sediments, terrestrial and aquatic vegetation, and aquatic insects. Selenium concentrations in aquatic plants and insects ranged from 2 to 310 ppm and were about 10 to 290 times those found at Volta. Concentrations in waterfowl food plants and insects at Kesterson were as high as 64 times greater than those reported to be a health hazard to birds. Seasonal variations in selenium concentrations were observed in some plants, but few consistent seasonal patterns were observed in aquatic insects, and few differences in selenium accumulation were found among ponds. Distribution of selenium in plant parts was not uniform during a growing season, as rhizomes contained higher concentrations than seeds. Most biota bioaccumulated selenium to levels greater than 1000 times the concentration in water, some nearly 5000 times. Mean concentrations of boron in aquatic plants and insects were usually 2 to 52 times those at Volta. Concentrations of other trace elements (i.e. arsenic, cadmium, chromium, copper, lead, mercury, molybdenum, and nickel) at Kesterson were too low to be toxic to biota.

Impacts of Agricultural Drainwater and Contaminants on Wetlands at Kesterson Reservoir, California

by

Carol A. Schuler

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for
the degree of

Master of Science

Completed April 15, 1987

Commencement June 1987

APPROVED:

Redacted for Privacy

Professor of Fisheries and Wildlife in charge of major

Redacted for Privacy

Head of Department of Fisheries and Wildlife

Redacted for Privacy

Dean of Graduate School

Date thesis is presented: April 15, 1987

ACKNOWLEDGEMENTS

I would like to thank my major professor, Robert G. Anthony for his advice, guidance and encouragement throughout this project. I would also like to thank E. Charles Meslow for his encouragement when needed.

I wish to greatly thank Susan Haseltine and James Fleming of the U.S. Fish and Wildlife Service, Patuxent Wildlife Research Center for encouraging me to come back to school and for finding funding for this research. I also give special appreciation to Harry M. Ohlendorf of Patuxent Wildlife Research Center, Davis California Field Station for providing guidance, assistance, and technical support. In addition, I would like to thank Patuxent Wildlife Research Center for providing funding for this research.

I acknowledge the staff of the U.S. Fish and Wildlife Service, San Luis National Wildlife Refuge and California Fish and Game, Los Banos Wildlife Management Area for their assistance and for access to study sites. I also would like to thank the Los Banos Wildlife Management Area for providing housing while I was in the field.

Special appreciation goes to Theresa Rhew, Tom Haensly, and Robert L. Altman for providing field and laboratory assistance. I also wish to thank Robert G. Anthony, Robert L. Altman, Roger L. Hothem, and Harry M. Ohlendorf for their reviews of the thesis.

I very special thanks goes to Robert L. Altman for providing much needed moral support and for always being there when I needed him. Special appreciation also goes to my friends in the Fisheries and Wildlife Department, Oregon State University for their friendship and support.

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I. General Introduction

High agricultural productivity in the San Joaquin Valley of California (Figure 1) is dependent on intensive irrigation. The Valley comprises approximately 500,000 ha of farmland and generally receives less than 25 cm of rain a year with most of the rain coming in the winter; consequently, most of the irrigation water must be imported (U.S. Bureau of Reclamation 1984a). An unavoidable consequence of intensive irrigation is the continual addition of salts to the already naturally saline soils of California. Over many years, salts have accumulated to intolerable levels for most crops, and they must be leached out of soils by appyling gypsum (calcium sulfate) and large amounts of water to maintain productivity (San Joaquin Valley Interagency Drainage Program 1979). The gypsum removes plant inhibiting salts and other minerals from the topsoil and carries them downward with irrigation water.

Natural drainage of excess irrigation water from soils west of the San Joaquin River and trough areas of the San Joaquin Valley is inadequate due to nearly

Figure 1. Map of the San Joaquin Valley of California, including locations of the San Luis Drain, Kesterson Reservoir, and Volta Wildlife Management Area.

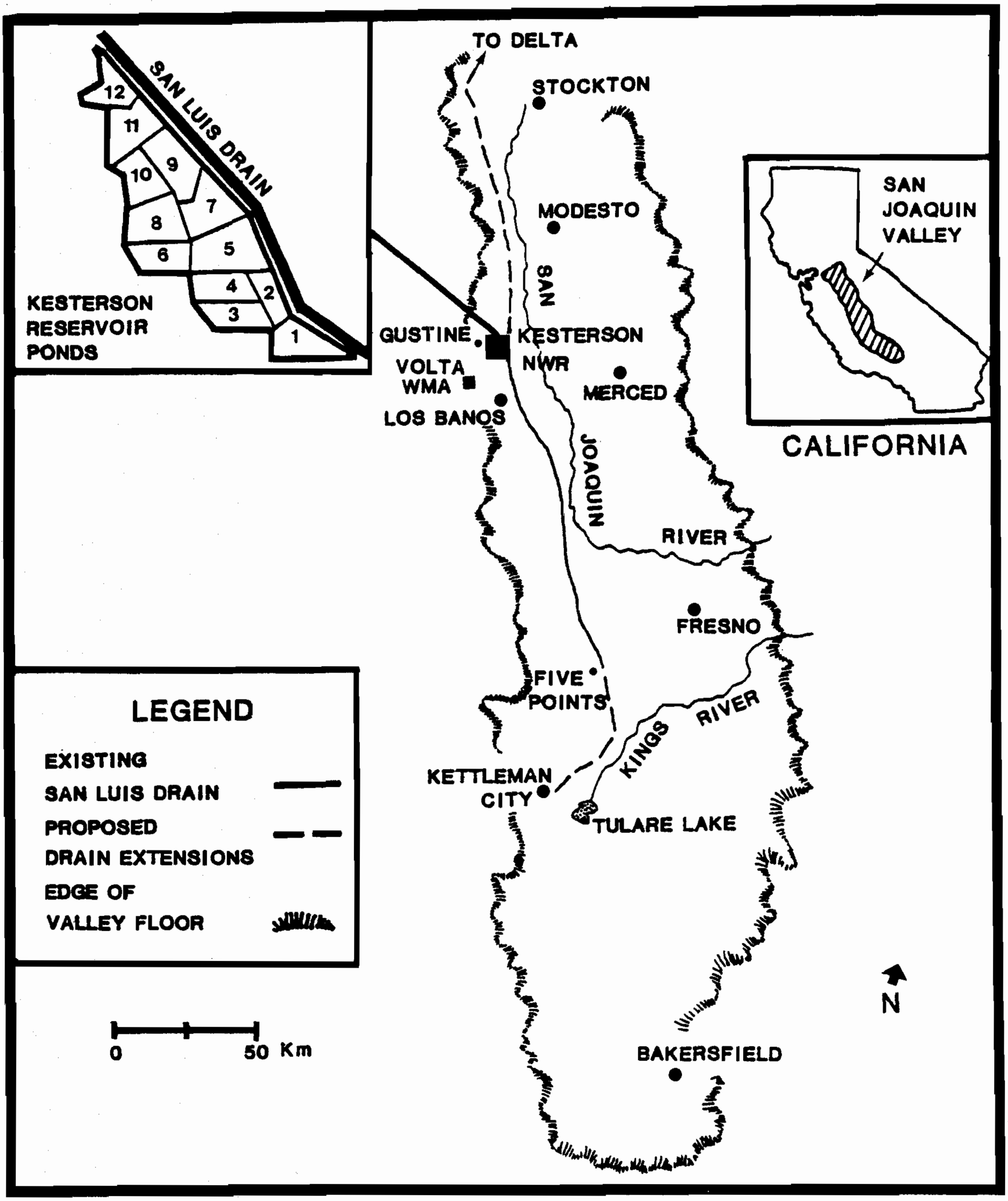
SAN LUIS DRAIN
12
11
10
9
8
7
6
5
4
3
2
1
KESTERSON
RESERVOIR
PONDS
TO DELTA
STOCKTON
MODESTO
SAN
JOAQUIN
RIVER
GUSTINE
KESTERSON
NWR
VOLTA
WMA
MERCED
LOS BANOS
FRESNO
FIVE
POINTS
KINGS
RIVER
KETTLEMAN
CITY
TULARE LAKE
BAKERSFIELD
SAN
JOAQUIN
VALLEY
CALIFORNIA
LEGEND
EXISTING
SAN LUIS DRAIN
PROPOSED
DRAIN EXTENSIONS
EDGE OF
VALLEY FLOOR
0
50 Km
N

Figure 1.

impermeable layers of clay at depths of 3 to 12 m (San Joaquin Valley Interagency Drainage Program 1979). Accumulation of salt and mineral laden water on the clay layers poses a serious threat to agricultural productivity, as ground water rises to the root zone (San Joaquin Valley Interagency Drainage Program 1979). Brackish waters now underlie about 160,000 ha of irrigated farmland with an additional 300,000 ha expected to develop drainage problems (San Joaquin Valley Interagency Drainage Program 1979). The initial solution to maintain agricultural productivity was installation of subsurface drainage tile systems to collect brackish ground water and transport it in a concrete lined collector drain constructed along the San Joaquin Valley to be discharged into the Sacramento-San Joaquin River Delta. Holding reservoirs were to be constructed along the drain to serve as evaporation ponds and to regulate flows in the collector drain. A secondary purpose was to create wetland habitat for waterfowl in the Valley.

By 1975, the U. S. Bureau of Reclamation had completed a 132 km segment of the collector drain known as the San Luis Drain from Five Points in Fresno County to Kesterson National Wildlife Refuge (Kesterson NWR) (Figure 1) (San Joaquin Valley Interagency Drainage Program 1979). By 1978, the San Luis Drain carried subsurface agricultural drainwater from approximately 3000 ha of farmland in Fresno County to Kesterson Reservoir (Kesterson), a system of 12 interconnecting evaporation ponds (500 ha) on the southern section of the 2400 ha Kesterson NWR (Figure 1) (U.S. Bureau of Reclamation 1984b, 1986). Kesterson was established in 1969 and is jointly managed by the U.S. Fish and Wildlife Service and U.S. Bureau of Reclamation. The reservoir was designed to regulate water flows, but became a storage and evaporation facility and secondarily a wildlife refuge. Between 1978 and 1984, these ponds received about 8.6 million cubic meters (7000 acre feet) of subsurface drainage water annually (U.S. Bureau of Reclamation 1986).

Ives et al. (1977) suggested evaporation ponds could be an asset in creating new wetland habitat and that subsurface agricultural drainwater could be further used in wetland management, because existing wetlands suffer from inadequate water supplies. Wetland habitat in the San Joaquin Valley has decreased dramatically, and the U.S. Fish and Wildlife Service (1978) estimates that less than 8 percent of the original wetland habitat remains. The number of ducks which inhabit the Valley is small compared to the millions that once wintered there. However, approximately 60 percent of the ducks and geese of the Pacific Flyway population and 18 percent of the Continental population overwinter each year in the Central Valley of California (Gilmer et al. 1982).

In 1982, the U.S. Fish and Wildlife Service began an investigation to determine the feasibility of using subsurface agricultural drainwater from the San Luis Drain for managing wetland habitat (Ohlendorf et al. 1986a). Collections of mosquitofish (*Gambusia affinis*) from Kesterson revealed concentrations of selenium nearly 100 times greater than samples from the nearby Volta Wildlife Management Area (Ohlendorf et al. 1986a). Presser and Barnes (1985) found that subsurface agricultural drain water entering the San Luis Drain contained from 140 to 1400 ppb selenium. Thus, selenium was being transported to Kesterson via drainwater in the San Luis Drain.

Selenium is a naturally occuring trace element in soils on the west side of the San Joaquin Valley. It has accumulated on the Valley floor from erosion of marine soils found in parts of the Coast Range of California (U.S. Bureau of Reclamation 1984b). When croplands are irrigated, selenium, along with excess salts and other minerals, is leached from soils into subsurface agricultural drainwater.

Observations by Ohlendorf et al. (1986a, 1986b) in the spring of 1983 and 1984 revealed low reproductive success in aquatic birds nesting at Kesterson. They found a high frequency of mortality and abnormalities in embryos and chicks of American coots (*Fulica americana*), eared grebes (*Podiceps nigicollis*), black-necked stilts (*Himantopus mexicanus*), and ducks (*Anas* spp.). Abnormalities included deformities of the eyes, legs, wings, feet, beak, brain, heart, liver, and skelton. Low reproductive success and abnormalities in embryos were associated with extremely high concentrations of selenium in these species. Mean selenium concentrations in bird eggs and livers at Kesterson were 2 to 22 times normal concentrations from a nearby control area (Ohlendorf et al. 1986b, Ohlendorf et al. 1987, T.S. Presser and H.M. Ohlendorf in prep.). Ohlendorf et al. (1986b) found a positive correlation between incidence of embryotoxicity and selenium concentration in eggs.

Observations of coots at Kesterson in 1984 (Ohlendorf et al. 1986b, Ohlendorf 1987) showed more extreme effects of selenium than were observed in 1983. Nearly 100 coot nests were located in 1983, but coots failed to nest in 1984, although numbers of adult birds were similar to 1983. Instead, many dead or moribund coots were observed, and selenium toxicosis was diagnosed in birds shot and found dead. Analysis of adult coot livers revealed significantly higher selenium concentrations in 1984 (82 ppm) than in 1983 (43 ppm), while Volta samples averaged less than 6 ppm. Body weights of coots were also significantly lower in 1984 than in 1983 and averaged about 25 percent lower than normal body weight (Ohlendorf 1987). Changes in concentrations of selenium from 1983 to 1984 indicate that coots were accumulating higher levels of selenium over time.

Reduced reproductive success and abnormal development of embryos, similar to abnormalities observed at Kesterson, have been reported in chickens and quail fed a diet containing 5 to 10 ppm selenium (Arnold et al. 1973, Ort and Latshaw 1978, El-Begearmi et al. 1977). In comparison, aquatic vegetation, invertebrates, and fish collected at Kesterson contained mean concentrations of selenium that ranged from 22 to 175 ppm (dry weight), while similar items at Volta contained less than 2 ppm (Ohlendorf et al. 1986a). Ohlendorf et al. (1986a) concluded that birds at Kesterson were consuming a diet high in selenium, and selenium concentrations were greater than those necessary to cause reproductive problems. Mortality, embryo abnormalities, and failure to nest have been attributed to selenium toxicosis (Ohlendorf 1987).

The objectives of this study were to (1) describe aquatic vegetation and invertebrate communities at Kesterson Reservoir and Volta Wildlife Management Area; (2) estimate abundance of vegetation, seeds, and invertebrates important to waterfowl; (3) determine selenium and other trace element concentrations in the aquatic and terrestrial ecosystem; and (4) characterize the bioaccumulation of selenium and other trace elements in wetlands and waterfowl foods.

II. Influence of agricultural drainwater on aquatic plant and invertebrate communities at Kesterson Reservoir, California.

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II. Influence of agricultural drainwater on aquatic plant and invertebrate communities at Kesterson Reservoir, California.

INTRODUCTION

Kesterson Reservoir (Kesterson) serves as a storage and evaporation facility for subsurface agricultural drainwater and is located on Kesterson National Wildlife Refuge (Kesterson NWR) in Merced County within the San Joaquin Valley of California (U.S. Bureau of Reclamation 1984b). Kesterson is the terminus for the San Luis Drain, a concrete-lined canal that transported subsurface agricultural drainwater from farmland in western Fresno County (U.S. Bureau of Reclamation 1984a). Drainwater effluent from farmland is often high in minerals, nutrients, and other elements (i.e. boron, chloride, nitrogen, phosphorous) (Johnston et al. 1965, Brown et al. 1974, Thomas and Crutchfield 1974, Olness et al. 1975, Miller et al. 1978, Miller et al. 1984). Johnston et al. (1965) found that large percentages of nutrients in applied fertilizers were lost in tile drainage effluent from irrigated lands in the San Joaquin Valley of California. Drainwater in the San Luis Drain contained high concentrations of nitrogen, chloride, sulfate, calcium, magnesium, and sodium, while samples from control areas had considerably lower concentrations (Presser and Barnes 1985). In addition to high salts and nutrients, subsurface drainwater entering the San Luis Drain was reported to contain 140 to 1400 ppb selenium in 1983, while surface drainwater and surrounding irrigation waters contained less than 10 ppb (Presser and Barnes 1984). Water discharged into Kesterson contained about 300 ppb selenium (Presser and Barnes 1984, Ohlendorf et al. 1986a) and had a high salinity (15000 umhos/cm) (Ives et al. 1977).

Reduced reproductive success in aquatic birds and a high incidence of mortalities and abnormalities in embryos were observed in 1983 and 1984 in aquatic birds nesting at Kesterson. Analysis of samples collected from Kesterson revealed elevated concentrations of selenium in aquatic plants, invertebrates, and bird tissues and eggs (Ohlendorf et al. 1986a, Ohlendorf et al. 1987b, Ohlendorf et al. 1987). Mean concentrations of selenium in aquatic bird livers was about 2 to 16 times greater at Kesterson than concentrations found at Volta Wildlife Management Area (Volta), a nearby control site. Waterfowl food organisms contained 12 to 130 times the concentrations of selenium found in food items from Volta. Mean concentrations of selenium in aquatic macrophytes, aquatic invertebrates, and fish collected in Kesterson ponds ranged from 22 to 175 ppm (dry weight), while those food items at Volta had concentrations less than 2 ppm (Ohlendorf et al. 1986a). Selenium concentrations of 5 to 10 ppm in the diet have been shown to reduce hatching success in chickens and quail and cause embryonic abnormalities similar to those seen at Kesterson (Arnold et al. 1973, Ort and Latshaw 1978, El-Begearmi et al. 1977, Heinz et al. in press). The study by Ohlendorf et al. (1986a) provides evidence that selenium is responsible for low reproductive success in aquatic birds at Kesterson.

The Central Valley of California is an important wintering site for 60 percent of the Pacific Flyway waterfowl population (Gilmer et al. 1982). In addition, the Valley provides important breeding habitat for several species of waterfowl (Kozlik 1974). However, waterfowl habitat is rapidly decreasing due to difficulties in obtaining sufficient quantities of water for wetlands (Gilmer et al. 1982). Consequently, Ives et al. (1977) suggested use of subsurface agricultural drainwater to create and manage wetlands for waterfowl. Construction of large drainwater storage sites and uses of this water on wetlands would provide accessible and attractive wetland habitat for waterfowl. It is important, therefore, to understand the response of wetland habitats to this water source. Past research has indicated that chemical and physical regimes of aquatic habitat dictate the plant and invertebrate communities they will support (Hynes 1960, Woodwell 1970, Hawkes 1979, Whitton 1979, Mason 1981), including the composition, quality, and quantities of potential waterfowl foods (Krapu 1974, Swanson et al. 1974, Serie and Swanson 1976, Swanson et al. 1984).

This study characterizes aquatic plant and invertebrate communities, relates habitat characteristics to various chemical and physical measurements, assesses availability of potential waterfowl foods, compares plant and invertebrate composition and abundance at Kesterson to a control area, and evaluates seasonal abundance of plants and invertebrates. The results provide information on the type of aquatic habitat that subsurface agricultural drainwater from seleniferous soils in California will support.

STUDY AREA

Kesterson NWR lies near the northwest corner of California's semi-arid San Joaquin Valley, approximately 8 km east of Gustine in Merced County (Figure 1). Kesterson Reservoir is located in the southern section of the refuge and consists of 12 evaporation ponds (average depth-1.2 m), totaling 500 ha (Figure 1). Kesterson is the terminus for the San Luis Drain and between 1978 and 1984 received approximately 8.6 million cubic meters (7000 acre feet) of subsurface agricultural drainwater annually, from about 3000 ha of farmland in western Fresno County (U.S. Bureau of Reclamation 1986). Drainwater was discharged from the San Luis Drain into the most southerly ponds (Ponds 1 and 2) and flowed generally northwest to the other ponds. There was a general trend of increasing salinity from pond 1 to pond 12, with the lowest salinity levels occuring in the first ponds (Saiki 1986b). Ponds 2, 7, and 11 were selected for this study to include the range of salinity at Kesterson.

Volta Wildlife Management Area, located approximately 10 km southwest of Kesterson (Figure 1) was selected as a control site. Volta encompasses about 1130 ha of seasonly flooded wetlands and consists of 36 ponds managed as waterfowl habitat (Appendix A). Volta receives most of its water supply from the Delta-Mendota Canal, which does not carry subsurface drainwater. Pond 5 was used as the control pond (Appendix A). Water depth was maintained at 30 to 60 cm all year, except for the period from mid-June to mid-August when drainage and evaporation reduced the pond to a mudflat.

Ponds at Kesterson and Volta consisted of large open water areas dominated by aquatic macrophytes, areas of dense emergent vegetation, and small islands that supported terrestrial grasses and forbs. At Kesterson, density of aquatic emergent vegetation was greatest in the more southerly ponds (i.e. ponds 1, 2, 3, 4) and diminished in northern ponds until there was little growth of emergent vegetation.

METHODS

Aquatic vegetation and invertebrates were sampled during May, August, and December of 1984 to quantify site, seasonal, and pond variation in biomass. Ponds 2, 7, and 11 at Kesterson and pond 5 at Volta (control) were sampled in May, while only ponds 2 and 5 were sampled in August and December, because study areas in ponds 7 and 11 were dry during those months. All samples were collected within a 10 day period during each sampling month.

Two 200 m long permanent transects were established in each pond to sample submergent and emergent plants and aquatic invertebrates. Transects were selected to represent characteristic vegetation in each pond. Twenty-five 0.1 m^2 plots were sampled along each transect, providing for 50 plots per pond per season, for a total of 400 plots over all three seasons. Plots were located from points systematically placed 8 m apart along a transect. The first point was located randomly between 1 and 8 m from the beginning of a transect. At each point a random compass direction and a random distance of 1 to 3 m was selected to provide the location of a plot.

Samples were collected in a vertical net constructed of 250 um mesh nylon fabric, attached to a heavy metal square frame that was sized to produce a 0.1 m^2 plot. In this way plants, seeds, and invertebrates in the water column and on the soil surface could be sampled at the same time. At each plot the sampling frame was tossed out and sank rapidly to the bottom into the upper 2 to 4 cm of soil. Submergent vegetation within the frame was pulled up and emergent vegetation was cut at the sediment surface, and a board was slid under the sampling frame to trap all materials inside the net. This technique was modified in dense cattail stands. Cattails were collected in separate plots and on separate days from the invertebrates and other plants, to minimize disturbance to invertebrates. Cattails were clipped in an open wire frame, and other plants and invertebrates were collected in the net frame dropped between cattails. All samples were drained of water, rinsed in a 500 um sieve, and stored in plastic bags in 70 percent ethanol. Cattails were rinsed, air dried, and stored in paper bags. Water depth to sediment surface was measured at each plot.

Samples were sorted by vegetation and seed species, and invertebrate families. Only those plants and invertebrates that appeared to dominate the area, were a species indicated by the literature to be a potential waterfowl food (Serie and Swanson 1976, Beam and Gruenhagen 1980, Connelly and Chesmore 1980, Pederson and

Pederson 1983, Euliss 1984), and/or occurred in esophagus samples (Appendix B) were sorted out of biomass samples. Esophagus contents of ducks collected by H.M. Ohlendorf in May-July 1983 and waterfowl collected by the authors in May, 1984 were stored in 70 percent ethanol and later examined to determine foods consumed on both study areas (Appendix B).

Plants and seeds were dried in a forced draft air oven for 72 hours at a temperature of 65°C, and invertebrates were dried at 55°C for 48 hours. Dry weights were determined to the nearest 0.001 g on a Mettler balance. Weights less than 0.001 g were recorded as trace (tr) and a value of 0.0001 g was used in calculations. All data values were converted from g/0.1 m^2 to g/m^2. Plant and invertebrate biomass was used as a measure of relative abundance. The biomass of potential waterfowl food items were quantified to asess food availability in the ponds. Abundance ratios of major food groups (i.e. vegetation, seeds, and invertebrates) were examined using percentages and actual dry weights of the overall combined groups.

All plants and invertebrates encountered in ponds, areas surrounding ponds, and islands within ponds at Kesterson and Volta, in addition to those in biomass samples, were recorded. All these species were given a subjective abundance rating: absent, rare, occasional, common, and abundant.

Water samples were collected from each pond during each sampling season to measure conductivity, pH, alkalinity, and boron and selenium concentrations. Water chemistry analyses were conducted by the Cooperative Chemical Analytical Laboratory, U.S.D.A. Forest Service, Corvallis, Oregon. Selenium and boron concentrations were determined by the U.S. Fish and Wildlife Service, Columbia Fisheries Research Laboratory, Columbia, Missouri.

Single day waterfowl censuses were conducted in May, August, and December at both study areas to determine the extent of waterfowl use of the areas (Appendix C).

Statistical Methods

Comparisons and descriptions of Kesterson and Volta based on transect data refers only to the areas of transects within the ponds not to the entire pond because of high sample variability, inadequate coverage of the entire ponds, and differences in habitat structure.

Arithmetic means, 95 percent confidence intervals, and percent occurrences were calculated from biomass samples by species, pond, and season. All analyses were conducted with the two transects in a pond combined because results were not significantly ($P<0.05$) altered when data were analyzed for each separate transect. A two-way analysis of variance was used to test for differences among ponds, seasons, and transects. Differences between pond and season means were separated by a Student-Newman-Keuls Multiple Range test (Snedecor and Cochran 1980). Simple correlations ($P<0.05$) were used to examine the relationship between chemical and physical variables and abundance of plants, seeds, and invertebrates in aquatic biomass samples (Appendix D). To determine if there was a relationship between aquatic communities and limnologic characteristics, a stepwise multiple regression procedure was used in which aquatic components were regressed against limnological variables (Appendix D). Differences were judged to be significant at the 0.05 level.

RESULTS

Plants

A total of 14 plant species were found in biomass samples at Kesterson and 13 species at Volta, including those species only occurring as seeds (Table 1). High variability in the biomass of the samples was found, which made interpretations more difficult. Total plant biomass was significantly ($P<0.05$) greater at Kesterson than at Volta and greater in August than May or December for both Kesterson and Volta, and lower in May at Kesterson. The most dominant plant species at Volta were horned pondweed (*Zannichellia palustris*) and cattails (*Typha domingenisus*), while Kesterson was dominated by widgeongrass (*Ruppia maritima*), cattails, and saltgrass (*Distichlis spicata*). Biomass of widgeongrass, horned pondweed, cattails, and saltgrass was significantly ($P<0.05$) greater at Kesterson than at Volta, with some overlap between ponds. The most evident submergent species at Kesterson was widgeongrass, with scattered areas of horned pondweed. Horned pondweed was the dominate submergent species at Volta, and widgeongrass was never encountered in Volta ponds. Cattails were the most dominant emergent species in pond 2 at Kesterson and at the Volta pond. No cattails occurred in samples from

Table 1. Mean biomass (g/m^2), 95 percent confidence intervals, and percent occurrences of plants, seeds, and invertebrates in aquatic habitats at Kesterson Reservoir and Volta Wildlife Management Area, 1984.

Item	Mean [% Occurrence] (± 95% Confidence Interval)							
	Volta			Kesterson				
	Pond 5			Pond 2			Pond 7	Pond 11
	May	Aug	Dec	May	Aug	Dec	May	May
Vegetation								
*Ruppia maritima (Widgeongrass)	--^{a}	--^{a}	--^{a}	0.90^{b}[8] (1.49)	3.91^{b}[18] (4.22)	tr^{a}[2]	8.59^{b}[18] (8.50)	64.13^{c}[70] (18.69)
*Zannichellia palustris (Horned Pondweed)	3.34^{b}[100] (1.01)	12.85^{c}[100] (3.82)	2.75^{b}[100] (1.27)	0.15^{a}[2] (0.30)	1.69^{a}[14] (1.73)	0.04^{a}[2] (0.08)	13.08^{c}[6] (16.70)	--^{a}
Typha domingenisus (Cattails)	209.52^{b}[14] (114.93)	235.87^{b}[41] (155.21)	164.85^{b}[38] (72.88)	269.47^{b}[46] (147.25)	365.20^{c}[48] (214.79)	312.49^{c}[48] (169.95)	--^{a}	--^{a}
*Juncus textilis Rush	4.34 [4] (6.13)	1.90 [3] (3.86)	1.80 [2] (3.62)	--	--	--	0.77 [4] (1.43)	7.56 [4] (12.40)
*Scirpus maritimus var. paludosus (Alkali Bulrush)	--	--	--	--	0.41 [2] (0.82)	--	--	--
Elymus triticoides (Rye Grass)	--	--	--	--	0.23 [2] (0.46)	0.04 [2] (0.08)	5.05 [2] (10.15)	--
Distichlis spicata (Saltgrass)	--^{a}	--^{a}	1.91^{a}[2] (3.84)	88.60^{b}[96] (29.65)	113.68^{b}[98] (27.28)	96.37^{b}[100] (23.90)	284.00^{c}[96] (60.66)	97.01^{b}[58] (34.55)
Total Vegetation	217.19^{ab} (114.07)	182.48^{ab} (175.70)	171.30^{a} (72.00)	359.12^{abc} (138.05)	485.14^{c} (203.81)	408.94^{bc} (163.57)	311.48^{abc} (55.07)	170.21^{a} (24.68)
Seeds								
*Ruppia maritima (Widgeongrass)	tr^{a}[2]	tr^{a}[8]	tr^{a}[4]	0.08^{a}[72] (0.08)	1.63^{b}[10] (1.27)	0.79^{a}[78] (0.56)	0.35^{a}[26] (0.46)	2.62^{b}[82] (0.96)
*Zannichellia palustris (Horned Pondweed)	0.06^{a}[94] (0.02)	0.56^{b}[100] (0.12)	0.05^{a}[96] (0.02)	tr^{a}[10]	0.03^{a}[22] (0.02)	0.08^{a}[32] (0.12)	0.11^{a}[16] (0.14)	tr^{a}[26]

Table 1. Continued.

*<u>Scirpus maritimus</u> var. paludosus (Alkali Bulrush)	tr^{a}[4]	tr^{a}[6]	tr^{a}[10]	tr^{a}[12]	tr^{a}[18]	0.03^{b}[50] (0.02)	tr^{a}[4]	tr^{a}[2]
*<u>Eleocharis macrostachya</u> (Spike-rush)	0.06^{b}[88] (0.02)	0.14^{b}[100] (0.06)	0.01^{a}[46] (0.01)	--^{a}	--^{a}	--^{a}	--^{a}	--^{a}
*<u>Heleochla schoenoides</u> (Swamp Timothy)	tr[12]	tr[3]	--	--	--	--	tr[4]	tr[2]
*<u>Atriplex patula</u> (Fathen)	--^{a}	--^{a}	tr^{a}[2]	tr^{a}[46]	tr^{a}[54]	0.01^{ab}[60] (0.01)	0.03^{b}[48] (0.02)	tr^{a}[6]
*<u>Rumex pulcher</u> (Fiddle Dock)	tr[2]	tr[11]	--	0.01[38] (0.01)	tr[14]	0.07[22] (0.12)	0.04[40] (0.03)	tr[6]
*<u>Rumex crispus</u> (Curly Dock)	tr[2]	tr[3]	tr[2]	tr[20]	0.04[26] (0.08)	0.14[14] (0.28)	0.13[46] (0.10)	tr[8]
*<u>Cressa truxillensis</u> (Alkali Weed)	tr^{a}[2]	tr^{a}[3]	--^{a}	--^{a}	--^{a}	--^{a}	0.01^{a}[24] (0.01)	1.14^{b}[94] (0.52)
*<u>Melilotus indica</u> (Yellow Sweet-clover)	tr[4]	--	--	--	--	--	0.01[2] (0.01)	tr[2]
Total Seeds	0.12^{a} (0.04)	0.71^{ab} (0.16)	0.06^{a} (0.03)	0.10^{a} (0.08)	1.72^{b} (1.27)	1.12^{ab} (0.66)	0.68^{ab} (0.48)	3.77^{c} (1.03)
<u>Invertebrates</u>								
*Corixidae (Water boatmen)	0.09^{b}[92] (0.04)	0.09^{b}[94] (0.02)	0.02^{a}[86] (0.01)	tr^{a}[2]	--^{a}	tr^{a}[14]	0.01^{a}[62] (0.01)	0.01^{a}[72] (0.01)
*Notonectidae (Backswimmers)	0.01^{a}[20] (0.01)	0.18^{b}[58] (0.14)	--^{a}	--^{a}	--^{a}	--^{a}	tr^{a}[2]	tr^{a}[10]
*Chironomidae Larvae (Midges)	0.05^{b}[98] (0.02)	0.04^{ab}[97] (0.01)	0.09^{c}[98] (0.03)	0.02^{ab}[96] (0.01)	0.01^{a}[80] (0.01)	tr^{a}[52]	0.03^{ab}[96] (0.02)	0.09^{c}[98] (0.04)
*Stratiomyidae Larvae (Soldier Flies)	--^{a}	--^{a}	--^{a}	0.09^{a}[48] (0.06)	0.04^{a}[30] (0.02)	0.01^{a}[8] (0.01)	0.16^{b}[8] (0.04)	0.14^{b}[52] (0.08)

Table 1. Continued.

*Ephydridae Larvae (Shore Flies)	tr^{a}[2]	tr^{a}[37]	0.01^{a}[44] (0.01)	0.22^{c}[100] (0.06)	0.14^{b}[100] (0.04)	0.12^{b}[98] (0.03)	0.09^{b}[90] (0.06)	0.13^{b}[74] (0.11)
*Tabanidae Larvae (Horse Flies)	--	tr[3]	tr[4]	0.03[28] (0.02)	tr[2]	0.02[6] (0.03)	0.01[8] (0.01)	tr[2]
*Syrphidae Larvae (Flower Flies)	--	--	--	tr[2]	tr[4]	--	tr[2]	--
*Hydrophilidae Larvae & Adults (Water Beetles)	0.01^{ab}[48] (0.01)	tr^{a}[25]	0.02^{ab}[22] (0.01)	0.01^{ab}[13] (0.01)	0.03^{b}[26] (0.01)	0.03^{b}[23] (0.01)	0.06^{c}[37] (0.02)	0.06^{c}[38] (0.02)
*Dytiscidae Larvae & Adults (Diving Beetles)	tr[26]	0.01[22] (0.01)	0.01[30] (0.01)	0.01[43] (0.01)	tr[22]	0.01[19] (0.01)	0.02[39] (0.01)	0.01[27] (0.01)
*Libellulidae Nymphs (Dragonflies)	tr[2]	tr[3]	tr[2]	tr[8]	0.01[6] (0.01)	tr[2]	tr[8]	tr[2]
*Coenagrionidae Nymphs (Damselflies)	0.02^{b}[22] (0.02)	--^{a}	--^{a}	0.01^{a}[38] (0.01)	0.03^{b}[60] (0.01)	0.03^{b}[38] (0.01)	tr^{a}[2]	--^{a}
*Gastropoda (Snails)	0.29^{b}[78] (0.12)	0.40^{b}[50] (0.47)	0.09^{a}[44] (0.08)	--^{a}	--^{a}	--^{a}	--^{a}	--^{a}
*Amphipoda (Sideswimmers)	0.01^{b}[60] (0.01)	tr^{a}[3]	--^{a}	--^{a}	--^{a}	--^{a}	--^{a}	--^{a}
Total Invertebrates	0.49^{a} (0.14)	0.73^{b} (0.49)	0.23^{a} (0.10)	0.39^{a} (0.08)	0.27^{a} (0.06)	0.21^{a} (0.06)	0.39^{a} (0.08)	0.46^{a} (0.14)
Grand Totals	217.81^{ab} (114.09)	183.92^{a} (175.68)	171.60^{a} (71.97)	359.61^{abc} (137.99)	487.12^{c} (203.55)	410.28^{bc} (163.45)	312.55^{abc} (54.99)	174.44^{a} (24.42)

tr=<0.01 g.
--Not observed
N=50 for each pond and season
*Potential waterfowl foods.
^{a,b,c}Significance between means of an item is reported by the Student-Newman-Kuels Multiple Range test ($P<0.05$). Means not significantly different share the same letter and letters not in common indicate significance between those means. No letters behind means in a row, indicate that the means are not significantly different.

ponds 7 (although cattails did grow in parts of pond 7) and 11, and none grew in ponds 10-12. Cattail and total plant biomass at Kesterson decreased progressively from pond 2 to 11. Other aquatic emergents encountered in all ponds were rush (*Juncus textilis*) and alkali bulrush (*Scirpus maritimus* var. paludosus) although they grew only in small patches at Kesterson.

Kesterson had a greater mean biomass of seeds for most ponds than Volta, although not all the differences were significant (Table 1). Curly dock (*Rumex crispus*), fiddle dock (*Rumex pulcher*), and fathen (*Atriplex patula*) had greater biomass at Kesterson, while only appearing as traces at Volta (Table 1). Spike-rush (*Eleocharis macrostachya*) seeds were never observed at Kesterson, but were common in samples from Volta.

Many other plants and invertebrates were observed at Kesterson and Volta that were not found in biomass samples, and these species provide additional information on community structure (Table 2). Several aquatic plants were never or rarely encountered at Kesterson but were observed as occasional to abundant at Volta. These included duckweed fern (*Azolla filiculoides*), spike-rush, duckweed (*Lemna gibba*), knot grass (*Paspalum distichum*), willowweed (*Polygonum lapathifolium*), sego pondweed (*Potamogeton pectinatus*), and horned pondweed (Table 2).

Table 2. List of plants and invertebrates and their abundances observed and sampled at Kesterson Reservoir and Volta Wildlife Management Area from May to December, 1984.

Item	Common Name	Abundance Kesterson	Abundance Volta
Plants			
Submergent or Floating			
Chlorophyta (filamentous)	Green Algae	C[ab]	C[a]
Bacillariophyceae			
Nitzchia sigma	Diatoms	A[c]	U
* *Azolla filiculoides*	Duckweed Fern	U	O
* *Lemna gibba*	Duckweed	U	O
* *Potamogeton pectinatus*	Sego Pondweed	R[d]	C
* *Ruppia maritima*	Widgeon Grass	A	U
* *Zannichellia palustris*	Horned Pondweed	R	A
Emergent			
* *Eleocharis macrostachya*	Spike-Rush	U	O
Elymus triticoides	Rye Grass	O	O
Juncus textilis	Rush	O	C
Paspalum distichum	Knot Grass	U	O
* *Polygonum lapathifolium*	Willowweed	U	O
Scirpus acutus	Common Tule	R[d]	C
* *Scirpus maritimus* var. paludosus	Alkali Bulrush	C	C
Typha domingensis	Cattail	A[e]	A
Terrestrial			
Allenrolfea occidentalis	Iodine Bush	R	A
Aster exilis		O	O
* *Atriplex patula* var. hastata	Fathen	C	C
* *Atriplex semibaccata*	Australian Saltbush	C	C
* *Avena barbata*	Slender Wild Oats	R	R
Baccharis Douglasii		O	O
Baeria platycarpha	Goldfields	C	C
Bassia hyssopifolia		O	O
Brassica geniculata	Mustard	C	C
Bromus mollis	Soft Chess	C	C
Bromus diandrus	Ripgut Grass	O	O
Bromus rubens	Foxtail Chess	O	O
Calandrinia ciliata var. Menziesii	Desert Rock Purslane	R	U
Carduus nutans var. leiophyllus	Musk Thistle	U	C
Carduus pycnocephalus	Italian Thistle	O	O
Centaurea melitensis	Tocalote	O	O
Conium maculatum	Poison-Hemlock	U	C
* *Cotula cornopifolia*	Brass-Buttons	O	O
* *Cressa truxillensis* var. vallicola	Alkali Weed	A	A
Distichlis spicata	Saltgrass	A	C
Festuca megalura	Foxtail Fescue	O	O

Table 2. Continued.

	Frankenia grandifolia		A	A
	Geranium dissectum	Cranesbill	O	O
	Grindelia camporum	Gum Plant	C	C
*	*Heleochla schoenoides*	Swamp Timothy	O	A
	Heliotropium curassavicum	Heliotrope	O	O
*	*Hordeum depressum*	Barley	R	U
*	*Hordeum geniculatum*	Barley	O	O
*	*Lolium perenne*	English Rye	O	O
	Lythrum Hyssopifolia	Loosestrife	O	O
	Malva parviflora	Cheeseweed	O	O
*	*Melilotus indica*	Yellow Sweet-Clover	C	C
	Plantago Coronopus	Plantain	O	U
	Polypogon monspeliensis	Rabbit-foot Polypogon	C	C
*	*Rumex crispus*	Curly Dock	C	C
*	*Rumex pulcher*	Fiddle Dock	C	C
	Senecio vulgaris	Common Groundsel	C	U
	Sesuvium verrucosum	Sea-Purslane	O	U
	Solidago spp.	Goldenrod	O	O
	Spergularia media	Sandy-Spurrey	R	U
	Sporobolus airoides	Dropseed	O	O
	Suaeda fruticosa		C	C
	Thelypodium sp.		C	C
	Xanthium strumarium	Cocklebur	U	O
	Invertebrates			
	Insecta			
	Diptera			
*	Chironomidae	Midges	A	A
*	Ephydridae	Shore Flies	A	R
*	Sciomyzidae	Marsh Flies	U	R
*	Stratiomyidae	Soldier Flies	A	U
*	Syrphidae	Flower Flies	R	U
*	Tabanidae	Horseflies	C	R
	Coleoptera			
*	Curculionidae	Weevils	U	R
*	Dytiscidae	Diving Beetles	C	C
*	Hydrophilidae	Water Scavenger Beetles	C	C
	Emphemeroptera			
*	Baetidae	Mayflies	O	C
	Hemiptera			
	Belostomatidae	Giant Water Bugs	U	C
*	Corixidae	Water Boatmen	A	A
	Hebridae	Velvet Water Beetles	O	U
*	Notonectidae	Backswimmers	C	A
*	Saldidae	Shorebugs	R	R
	Lepidoptera			
	Noctuidae	Larval Moths	O	U
	Odonata			
	Anisoptera			
*	Libellulidae	Dragonflies	A	A
	Zygoptera			
*	Coenagrionidae	Damselflies	A	A
	Arachnoidea			

Table 2. Continued.

Hydracarina			
Eylaidae			
Eylais	Water Mites	U	R
Crustacea			
Cladocera			
* Daphnidae	Daphnia	A	A
Mysidacea			
Mysidae			
Neomysis	Oppossum Shrimp	U	R
* Amphipoda	Sideswimmers	U	A
* Ostracoda	Seed Shrimp	A	A
Annelida			
Hirudinea	Leeches	U	O
Oligochaeta	Aquatic Earthworms	C	O
Mollusca			
* Gastropoda	Snails	U	A

[a]Abundance Codes:
A - Abundant
C - Common
O - Occasional
R - Rare
U - Absent

[b]Never observed in Pond 2.
[c]Abundant in Pond 2, occasional in Pond 7 and Pond 11.
[d]Found only in Pond 2.
[e]Found only in Ponds 1 through 8
*Potential waterfowl foods

Widgeongrass was the only submergent never encountered at Volta that was a common aquatic in Kesterson ponds. Most of the terrestrial plant species occurred at both study sites but often with varying abundance (Table 2).

Diatoms (Nitzchia sigma) were found in large masses clinging to vegetation in pond 2 at Kesterson, in small areas of pond 7 and 11, but were never observed in ponds at Volta (Table 2). Filamentous green algae (Chlorophyta) was never observed in pond 2 at Kesterson, but occurred in large amounts in ponds 7 and 11, and limited amounts were observed in Volta ponds during May and August (Table 2).

Invertebrates

Eighteen families of invertebrates were observed or occurred in aquatic samples at Kesterson and 22 at Volta (Table 2). Volta not only had a greater number of invertebrate families, but also had more species in some families. Three species from each family of Corixidae (water boatmen), Dytiscidae (diving beetle larvae), and Libellulidae (dragonfly nymphs) were observed at Volta, while only one species was observed in each family at Kesterson. In addition, Volta had greater total biomass of invertebrates than Kesterson for all seasons, with a decrease in biomass during December for both study areas

(Table 1). Amphipoda (sideswimmers), *Eylais* (water mites), Gastropoda (snails), *Neomysis* (oppossum shrimp), Hirudinea (leeches), Belostomatidae (giant water bugs), and Sciomyzidae (flower fly larvae) occurred only at Volta (Tables 1, 2). Biomass of Dipteran families Ephydridae (shore fly larvae) and Stratiomyidae (soldier fly larvae) were significantly ($P<0.05$) greater in Kesterson ponds, but these families plus Tabanidae (horsefly larvae) and Syrphidae (flower fly larvae) were never or rarely observed at Volta (Tables 1, 2).

Water Chemistry

Conductivity and water depth were greater at Kesterson, while alkalinity was greater at Volta (Table 3). Conductivity and total dissolved solids (relative measures of salinity) indicated high salinity in Kesterson ponds, which was 4 to 13 times greater than levels at Volta (Table 3). Conductivity in May increased sequentially in ponds 2 to 11 at Kesterson. There was an increase in conductivity that followed a pattern of minimum concentrations during May (1122 umhos/cm at Volta and 7113 umhos/cm in pond 2 at Kesterson) and maximum levels during August at Kesterson (14245 umhos/cm) and December at Volta (1646 umhos/cm). Total alkalinity was about 2 times greater at Volta (292-367 ppm) than at

Table 3. Water chemistry of ponds at Kesterson Reservoir and Volta Wildlife Management Area in May, August, and December, 1984.

	Volta			Kesterson				
	Pond 5			Pond 2			Pond 7	Pond 11
Measurement	May	Aug	Dec	May	Aug	Dec	May	May
Alkalinity (ppm)[a]	292	304	367	171	167	175	158	200
pH[a]	8.4	7.8	8.6	7.8	8.1	8.3	8.9	8.8
Conductivity (umhos/cm)[a]	1122	1462	1646	7113	14245	11322	8017	10101
Total Dissolved Solids (ppm)[a]	898	1170	1317	5690	11396	9058	6414	8081
Selenium (ppb)[b]	ND[d]	ND	ND	91	193	46	78	37
Boron (ppm)[b]	2.20	1.40	1.82	16.00	16.37	12.30	19.00	20.67
Water Depth (cm)[c]	26.9	4.9	33.1	55.3	42.2	43.6	29.3	32.8

[a]N=1
[b]N=3 (mean)
[c]N=50 (mean)
[d]ND=Not detected.

Kesterson (158-200 ppm) (Table 3). The pH ranged from 7.8 to 8.9 with no apparent differences between Kesterson and Volta (Table 3). Water depth in pond 2 at Kesterson was significantly ($P<0.05$) deeper than the Volta pond and ponds 7 and 11 at Kesterson for all seasons. Selenium and boron concentrations were significantly greater at Kesterson than Volta, and there was a gradient of decreasing selenium and increasing boron concentrations from pond 2 (south) to pond 11 (north) in May (Table 3).

Alkalinity, conductivity, selenium, and boron concentrations were highly correlated with each other (Appendix D). Alkalinity was inversely correlated with conductivity ($r=-0.85$), selenium ($r=-0.73$), and boron ($r=-0.90$). Conductivity was positively correlated with selenium and boron ($r=0.80$ and 0.83, respectively). Selenium and boron were positively correlated at $r=0.65$. All other water chemistry variables were not correlated ($P>0.05$). Biomass of some plants and invertebrates were significantly ($P<0.05$) correlated with water chemistry parameters, although no consistent patterns occurred (Appendix D).

Waterfowl Foods and Abundance

All seeds and invertebrates, plus widgeongrass and horned pondweed were considered potential waterfowl foods. Plants were the most abundant foods, with the exception of pond 2 in December where seeds (82%) and invertebrates (15%) were more abundant (Figure 2). Biomass of seeds was significantly ($P<0.05$) greater than that of invertebrates at Kesterson, with the exception of pond 2 in May which had greater invertebrate biomass (Figure 3). In contrast, dry weights of seeds were significantly ($P<0.05$) lower than invertebrates at Volta in May and December. The biomass of seeds and invertebrates was similar in August at Volta. Overall, mean invertebrate biomass was significantly ($P<0.05$) greater at Volta than at Kesterson, while seed biomass was significantly ($P<0.05$) greater at Kesterson.

Larger numbers of ducks were present on Volta ponds in all seasons. Total number of ducks present on Volta in May, August, and December were 764, 11237, and 220, respectively and on Kesterson 114, 205, and 14 (Appendix C). In September of 1984, the U.S. Fish and Wildlife Service began a hazing program to scare waterfowl off Kesterson. Consequently, the waterfowl census in December was lower than normal use (San Luis National Wildlife Refuge, unpubl. data). Mallards (*Anas platyrhynchos*) (66% of the total population counted at Kesterson, 15% of the total population counted at Volta), gadwalls (*A. strepera*) (25%, 4%), common pintails (*A.*

Figure 2. Mean percentage of potential waterfowl food groups recovered in aquatic habitat biomass samples at Kesteron Reservoir and Volta Wildlife Management Area, 1984.

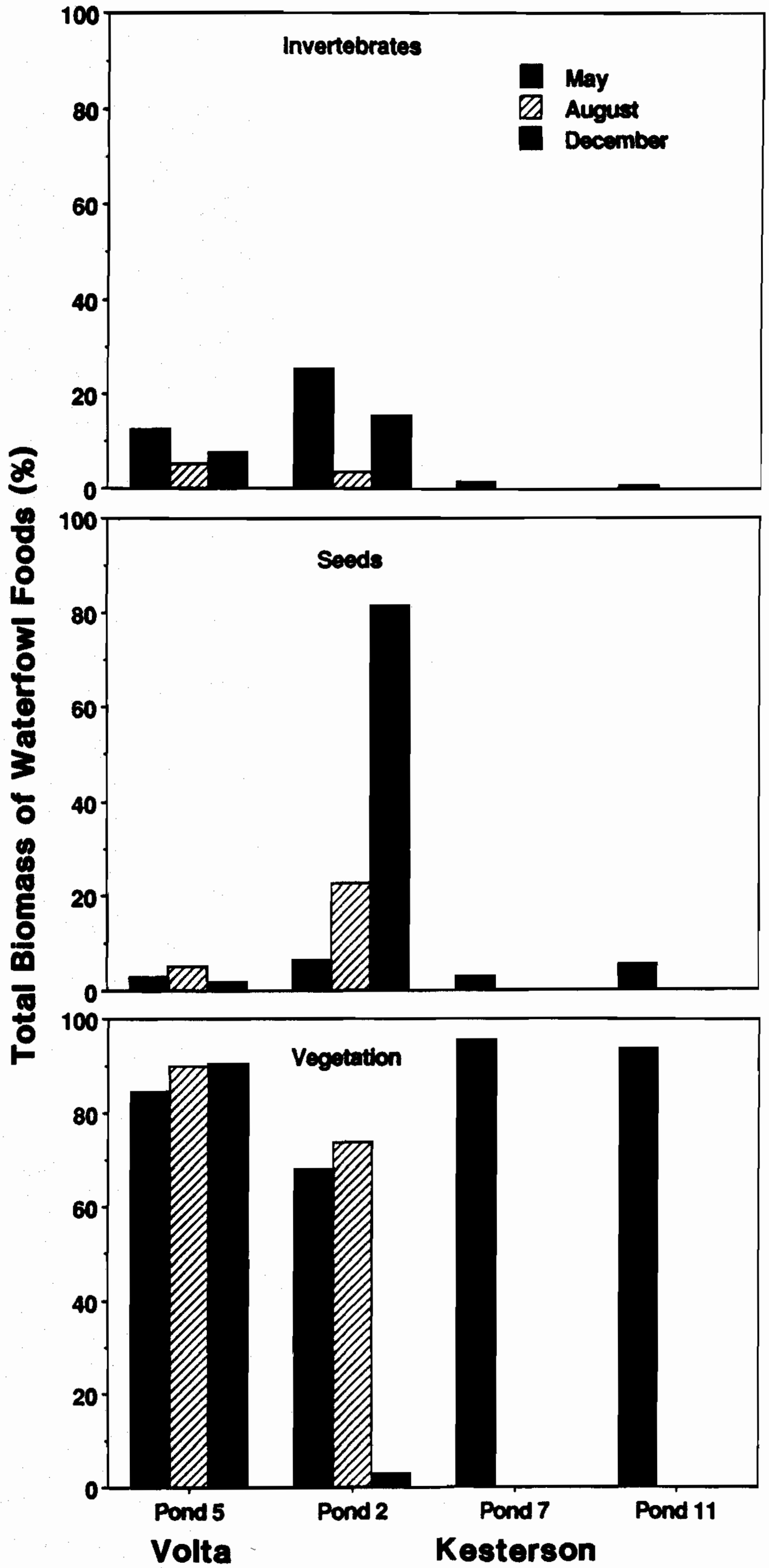
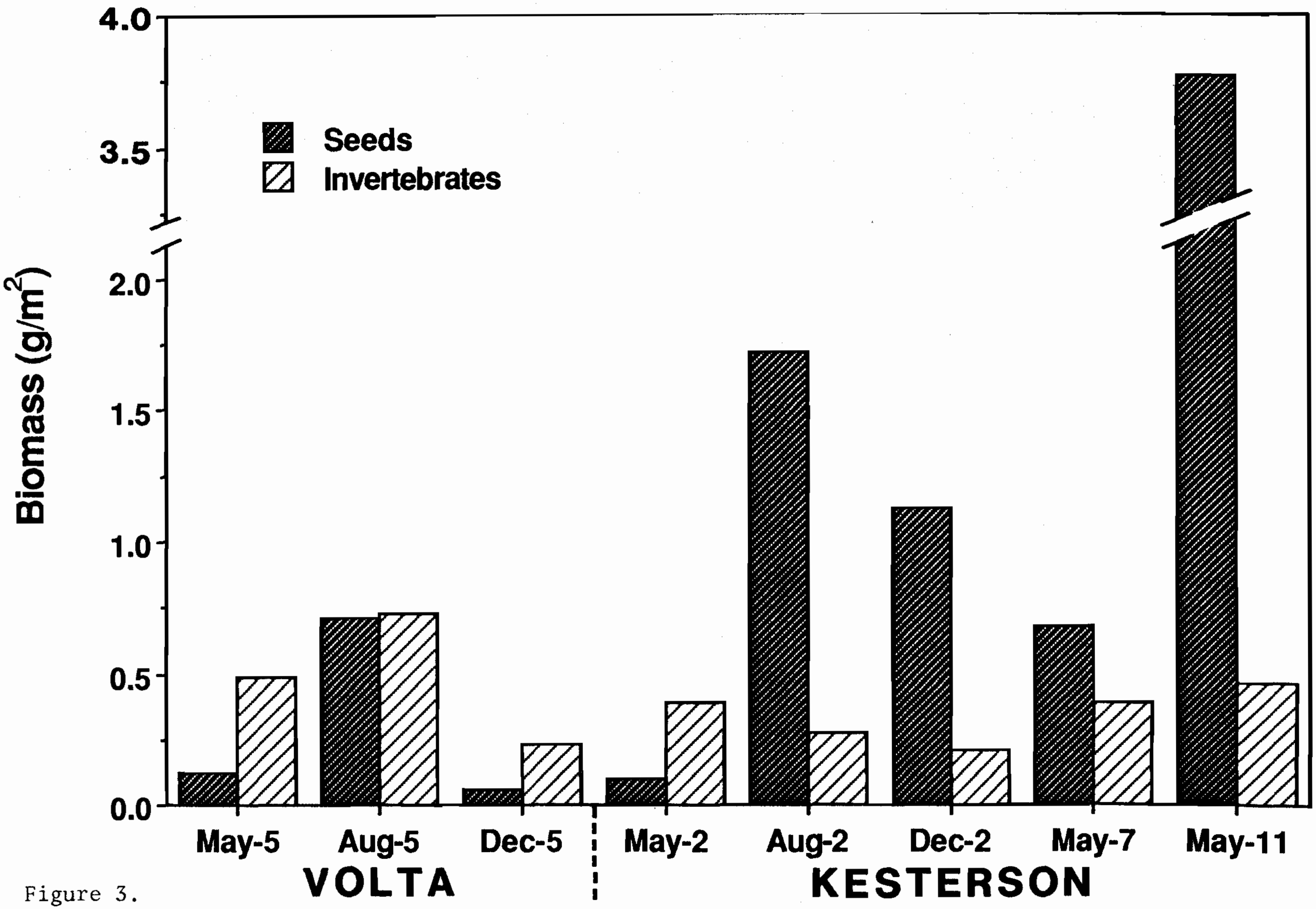

Invertebrates
May
August
December
Seeds
Vegetation
Total Biomass of Waterfowl Foods (%)
100
80
60
40
20
0
Pond 5
Pond 2
Pond 7
Pond 11
Volta
Kesterson

Figure 2.

Figure 3. Comparison of seed and invertebrate biomass found in aquatic habitat samples at Kesterson Reservoir and Volta Wildlife Management Area, 1984.



Seeds
Invertebrates
Biomass (g/m²)
4.0
3.5
2.0
1.5
1.0
0.5
0.0
May-5
Aug-5
Dec-5
May-2
Aug-2
Dec-2
May-7
May-11
VOLTA
KESTERSON

Figure 3.

acuta) (1%, 52%), green winged teal (*A. crecca*) (2%, 16%), cinnamon teal (*A. cyanoptera*) (2%, 4%), Northern shoveler (*A. clypeata*) (0%, 80%), and ruddy ducks (*Oxyura jamaicensus*) (0%, 80% during winter) were the most common species seen on Kesterson and Volta ponds, respectively (Appendix C).

DISCUSSION

Water Chemistry

Water at Kesterson was saline, had high selenium and boron concentrations, and had high concentrations of nutrients and salts as reported by Presser and Barnes (1985). In addition, there was a gradient of increasing salinity (similar pattern was reported by Presser and Barnes 1985, Saiki 1986b) and boron concentrations and decreasing concentrations of selenium and nitrogen (Presser and Barnes 1985) in the direction of water flow from pond 2 to pond 11.

High nutrient and salt concentrations in water systems have been reported to cause a shift in floral and faunal composition and abundance (Hynes 1960, Woodwell 1970, Cairns and Dickson 1972, Axelrad et al. 1981, Brennan 1985). Changes often include an increase in productivity of some plant and invertebrate species and a decrease in others, a decrease in higher plant and invertebrate diversity (Gunter 1961, Littler and Murray 1975, Hawkes 1979, Whitton 1979, Mason 1981), and an increase in algae production (Cairns and Dickson 1972, Axelrad et al. 1981, Charles 1985).

Plants

Salinity (Gunter 1961, Martin 1970) and nutrient levels (Mulligan and Baranowski 1969, Whitton 1970, Harlin and Thorne-Miller 1981, Charles 1985) have been shown to influence algal composition and production. Diatoms and filamentous algae were abundant at Kesterson but occurred only occassionally at Volta. Diatom populations of Nitzschia were very abundant in pond 2 at Kesterson, but abundance decreased drastically in the more northerly ponds (i.e. pond 11). This genus has been found to be more abundant in waters with high nitrogen levels or in heavily polluted waters (Turoboyski 1977, Whitton 1979). Distribution of filamentous algae at Kesterson was in contrast to that of diatoms; filamentous algae was not observed in pond 2, but was very abundant in ponds 7 and 11. Algal productivity was probably enhanced by high nitrogen levels at Kesterson, while distribution was limited by specific levels of salts. There is a species specific range of nutrient and salt enhancement that aids algae production and a level of extreme nutrient and salt pollution that suppresses populations (Fitzgerald 1969, Mason 1981).

Kesterson had a greater biomass of submergent and emergent vegetation and seeds than Volta. The plant species thriving at Kesterson appear to be tolerant of the associated water conditions, and distinct differences in the distribution of aquatic vegetation occurred in the two wetlands. Kesterson ponds supported dense stands of widgeongrass and some scattered areas of horned pondweed, while Volta was dominated by horned pondweed and other aquatic plants (i.e. sego pondweed, duckweed fern, spike-rush, willowweed, and duckweed) that never or rarely occurred at Kesterson. The highly saline environment at Kesterson is one probable determinant in causing the differences observed in plant composition. Many plant species are restricted by high salinity, while other species are salt resistant (Salisbury and Ross 1978), and distributions of several submergent macrophytes at Kesterson and Volta correspond with habitat descriptions in the literature. Widgeongrass has been described as a salt tolerant species and is usually found in brackish to saline water, horned pondweed in fresh to subsaline water, sego pondweed in fresh to occasional in brackish water (Mason 1957, Barbour 1970, Ungar 1974), and duckweed in freshwater (Mason 1957). More specifically, distributions of several species followed the salinity gradient at Kesterson (i.e. the lowest salinity in pond 2 and highest in pond 11). Sego pondweed survived only in small patches of pond 2, and cattail abundance decreased as salinity increased.

Nutrient levels in the water at Kesterson may also have played a role in macrophyte distribution and abundance, because nitrogen enrichment will enhance the production of some plant species but limit the overall diversity of the plant community (Ryther and Dunstan 1971, Nixon and Oviatt 1973, Broome et al. 1975, Valiela et al. 1975, Jeffries and Perkins 1977, Kingdig and Littler 1980). Valiela et al. (1975) and Orth (1977) found that maximum biomass of macrophytes in nitrogen enriched ponds was about 4 times that found in controls. They noted that several species did not survive in nitrogen treated ponds and with increased growth some species were able to outcompete others, causing a decline in species diversity. Although the same species of cattails were growing in Kesterson and Volta ponds, cattails at Kesterson had a greater biomass and showed more extensive growth and rapid spread over the three sampling seasons than cattails observed at Volta. This increased productivity is most likely a response to nutrient and boron enrichment in Kesterson ponds and is similar to results reported by Nixon and Oviatt (1973), Valiela and Teal (1974), Orth (1977), and Wells et al. (1980). They observed greater density of stems, taller plants, darker green foliage, longer leaves, and greater biomass of aquatic macrophytes growing in waters high in nutrients (particularly nitrogen). In addition, Boyd and Walley (1972) observed an increase in standing crop of cattails with increased levels of boron. Although cattails were more productive at Kesterson, they and other species (e.g. rushes) appeared in poorer condition and had browning tips and leaf edges, which is often an indication of a toxic response to an excess of an element (Salisbury and Ross 1978). Poor health and a decline in growth has been observed in some macrophytes grown in saline (Barbour 1970) or nitrogen enriched waters (Moss 1976), and browning leaf edges resembles injury from excess boron (Eaton 1944, Bingham and Garber 1970, Collier and Greenwood 1977).

Boron and selenium concentrations of greater than 16000 ppb and 50 ppb, respectively, were found in Kesterson water, and analyses of plant tissues showed high levels of both metals (Chapter III, Ohlendorf et al. 1986a). As with nutrients and salinity, levels of sensitivity and tolerance to boron and selenium to plants tends to be species specific (Eaton 1944, Rosenfeld and Beath 1964, Collier and Greenwood 1977, Brown and Shrift 1982, Maas 1986). The U.S. Environmental Protection Agency (1976) gives the water quality standard for selenium in drinking water at 10 ppb, and the standard for boron for long-term irrigation of sensitive crops is

750 ppb. Maas (1986) reported even lower threshold levels (for plants classified as very tolerant to boron) of 6-15 ppb boron in water, and Bradford (1966) stated that boron concentrations of 750 ppb in irrigation water caused injury to citrus crops. Furthermore, some plant species are intolerant of high selenium levels in the soils, while others are tolerant (Hamilton and Beath 1963, Brown and Shrift 1982). Eisler (1985) found that 47 to 53 ppb selenium was associated with growth inhibition and changes in species composition of freshwater algal communities. Both selenium and boron were higher at Kesterson than the reported water quality standards and greater than concentrations shown to cause injury to some plant species.

Invertebrates

Polluted waters are generally characterized by a reduction in invertebrate diversity and proliferation of a few species (Hynes 1960, Roback 1974, Hawkes 1979, Persoone and De Pauw 1979). Kesterson ponds supported a lower variety and abundance of invertebrates than Volta, which had more invertebrate families and more species of several families (e.g. Corixidae, Libellulidae). Several invertebrates, including Amphipoda, *Eylais*, Gastropoda, *Neomysis*, Hirudinea, and Belostomatidae were found at

Volta but were not observed at Kesterson. These taxa are reported to be sensitive to water pollution (Jolly and Chapman 1966, Persoone and De Pauw 1979, Marchant et al. 1984). In addition, Savage (1985) found a greater number of species of Gastropoda, Hirudinea, and Amphipoda in the freshwater areas, as compared to brackish water areas. Amphipoda distribution has been shown to be influenced by salinity intolerance (Dorgelo 1974, Savage 1982a).

Kesterson supported a greater abundance of Oligochaets (aquatic earthworms) and several families of Diptera (i.e. Ephydridae, Stratiomyidae, Tabanidae, Syrphidae) that were only occasionally observed at Volta. Dipteran flies from families Ephydridae, Syrphidae, and Tabanidae appear to be tolerant of low water quality conditions (Jolly and Chapman 1966, Brennan 1985), and Jetter (1975) found them to be abundant in mats of organic matter in ponds receiving water high in nutrients. Several authors describe Oligochaets as tolerant of pollutants (Jolly and Chapman 1966, Persoone and De Pauw 1979, Marchant et al. 1984), and Diptera have been reported to be the most tolerant of high concentrations of chloride (>1000 mg/l) (Roback 1974).

A greater abundance and species composition of Corixidae was encountered at Volta, and their biomass in all ponds was inversely correlated with conductivity.

Thus Corixid distribution at Kesterson was probably limited by high salinity. Corixids are restricted to a relatively narrow range of environmental conditions (Savage 1979, Savage 1982b), and Savage (1982b) also found a significant correlation between distribution and abundance of Corixids and conductivity of water bodies.

A greater abundance of invertebrates is often associated with denser stands of submergent vegetation (Krull 1970, Voights 1976). However, the dense submergent stands of widgeongrass at Kesterson contained a lower abundance of invertebrates, while Volta's low abundance of submergents had a greater abundance of invertebrates. These contrasting results may be due to the poorer water quality and higher salinity at Kesterson. Gunter (1961) identified salinity as a causative factor reducing productivity of invertebrates. High nutrient levels have also been shown to cause disappearance of sensitive species and increased abundance of tolerant species (Axelrad et al. 1981). Marchant et al. (1984) compared faunal composition of a site receiving saline and nutrient enriched water and found that control sites were richer in taxa and abundance of invertebrates than polluted sites. Furthermore, analysis of aquatic invertebrate tissues from Kesterson showed elevated selenium and boron concentrations (Chapter III, Ohlendorf et al. 1986a), and these high levels may be having a detrimental effect on survival, abundance, and composition.

Use of wetlands by waterfowl has been related to high invertebrate abundance (Arner et al. 1970). Waterfowl were more abundant at Volta than Kesterson, which may have been correlated with greater invertebrate food availability at Volta.

Comparisons of relative abundance and composition of fauna and flora between Kesterson and Volta provides an example of the aquatic biota that subsurface agricultural drainwater from seleniferous soils in California could support. Kesterson was found to have a greater abundance of vegetation and seeds but a lower abundance and species composition of invertebrates than Volta. Water quality at Kesterson appears to inhibit invertebrate production, enhance overall plant production, and encourage selective tolerant invertebrate families and plant species while discouraging others. There are many hypotheses as to the actual determinant that could produce the community structure and composition observed at Kesterson, several of which have been discussed in this paper. Community structure at Kesterson was most likely influenced by high concentrations of salts, nitrogen (Presser and Barnes 1985), and boron. The influence of high selenium levels is unknown but considering the extreme levels and its influence on higher trophic levels (Ohlendorf et al. 1986a), it may have had some effect on limiting plants and invertebrates. As waterfowl habitat, Kesterson supports a large food supply for birds, such as coots that feed on vegetation. However, Kesterson's quality as feeding habitat for other avian species appears to be greatly reduced due to greater water depths (dabbler ducks prefer shallower depths), lower invertebrate biomass, high salt levels, and overall poor water quality.

III. Selenium and other trace elements in wetlands and waterfowl foods at Kesterson Reservoir, California.

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III. Selenium and other trace elements in wetlands and waterfowl foods at Kesterson Reservoir, California.

INTRODUCTION

Selenium is a naturally occurring trace element in the soils of California and is leached into subsurface agricultural drainwater along with excess salts and other minerals (U.S. Bureau of Reclamation 1984b, Wiggett and Alfors 1986). It is an essential trace element in animal nutrition at low levels, but can be toxic at slightly higher concentrations (Rosenfeld and Beath 1964, National Research Council 1976, 1983, Wilber 1980). Selenium also bioaccumulates in the food chain, particularly via ingestion (Rosenfeld and Beath 1964, Lakin 1973, Sandholm et al. 1973, Fowler and Benayoun 1976, Wilber 1980, National Research Council 1983).

Kesterson Reservoir (Kesterson) served as a storage and evaporation facility for saline subsurface agricultural drainwater from farmlands in the western San Joaquin Valley of California (Figure 1). Water samples from Kesterson had selenium concentrations averaging about 300 ppb, while nearby areas contained less than 2 ppb (Presser and Barnes 1984, Ohlendorf et al. 1986a, Saiki 1986a, 1986b). In addition, the U.S. Environmental

Protection Agency (1976) has found that water containing selenium concentrations greater than 35 ppb could potentially be harmful to aquatic organisms. Collections of mosquitofish (*Gambusia affinis*) from Kesterson were found to contain selenium concentrations nearly 100 times those in samples from nearby Volta Wildlife Management Area (Volta) (Saiki 1986a, 1986b).

Low reproductive success and a high incidence of mortalities and abnormalities in embryos and chicks were observed in aquatic birds nesting at Kesterson (Ohlendorf et al. 1986a, 1986b, Ohlendorf 1987), and these conditions were associated with extremely high concentrations of selenium in bird tissues and eggs as well as food chain organisms. Livers of aquatic birds from Kesterson had mean selenium concentrations ranging from 20 to 127 ppm (dry weight), while birds from Volta had means of 4 to 9 ppm (T.S. Presser and H.M. Ohlendorf in prep.). Selenium concentrations of 5 ppm or more in the diet have been shown to reduce hatching success and cause embryonic abnormalities in chickens, quail, and mallards (Arnold et al. 1973, El-Begearmi et al. 1977, Ort and Latshaw 1978, Heinz et al. in press). These abnormalities were similar to those observed at Kesterson (Ohlendorf et al. 1986a). Aquatic bird foods (aquatic macrophytes and insects) contained 12 to 370 ppm selenium at Kesterson but less than 3 ppm at Volta (Ohlendorf et al. 1986a, Saiki 1986a, 1986b). Ohlendorf et al. (1986a, 1986b) concluded that aquatic birds at Kesterson ate a diet high in selenium and incorporated selenium into their tissues and eggs at levels high enough to cause reproductive failures.

The loss of nearly 95 percent of California's wetlands (Gilmer et al. 1982) has made it important to determine the impacts of using subsurface agricultural drainwater for wetland wildlife habitat. The purpose of this study was to characterize the bioaccumulation of selenium and other trace elements from subsurface agricultural drainwater in wetlands and waterfowl foods at Kesterson Reservoir.

STUDY AREA

Kesterson National Wildlife Refuge is located approximately 8 km east of Gustine, Merced County, in the northern portion of the San Joaquin Valley of California (Figure 1). Kesterson Reservoir is located in the southern section of the refuge and consists of 12 evaporation ponds (average depth-1.2 m), totaling about 500 ha (Figure 1). Kesterson is the terminus for the northern end of the San Luis Drain and received approximately 8.6 million cubic meters (7000 acre feet) of subsurface agricultural drainwater annually from 1978 to 1984 (U.S. Bureau of Reclamation 1986). Drainwater was discharged from the San Luis Drain into the most southerly ponds (ponds 1 and 2) and flowed northwest to the other ponds. Drainwater was saline and contained high concentrations of nutrients and several trace elements (Presser and Barnes 1985, Ives et al. 1977).

Volta Wildlife Management Area was used as a control or reference site and is located approximately 10 km southwest of Kesterson (Figure 1). Volta encompasses about 1130 ha of seasonly flooded wetlands and consists of 36 ponds (depth-30 to 60 cm) managed as waterfowl habitat (Appendix A). Volta received most of its water from the Delta-Mendota Canal, which was not contaminated by agricultural drainwater.

Kesterson and Volta were dominated by large areas of open water containing submergent vegetation and other areas with dense emergent vegetation. Vegetation at Kesterson was dominated by cattails (*Typha domingensis*) and widgeongrass (*Ruppia maritima*), and that of Volta was dominated by cattails and horned pondweed (*Zannichellia palustris*) (Chapter II).

METHODS

Samples were collected in May, August, and December of 1984 from ponds 2, 7, 11 at Kesterson and pond 5 at Volta. Samples of water; sediments; algae; diatoms; submergent aquatic, emergent aquatic, and terrestrial vegetation; aquatic and terrestial seeds; rhizomes of aquatic plants; and aquatic insects were collected for analysis of trace elements. Three replicate samples were collected from all study sites in each sampling season when available (not all samples were available every season in every study pond). All samples were analyzed for selenium and boron, and some of the samples also were analyzed for arsenic, cadmium, chromium, copper, lead, mercury, molybdenum, and nickel.

Water samples were filtered through 0.1 um millipore filters, acidified with ultrapure concentrated nitric acid to a pH less than 2.0, and stored in acid-rinsed polyethylene bottles at room temperature until analyzed. Sediments and plants were collected by hand; aquatic insects were collected in sweep nets and hand sorted into groups. Biota samples were placed in acid-rinsed glass jars except for large plant materials and sediments that were placed in plastic bags. Samples were frozen and stored 5 to 14 months prior to chemical analyses. All samples were analyzed by hydride generation-atomic absorption spectroscopy (Whetter and Ullrey 1978, U.S. Environmental Protection Agency 1983) at the Environmental Trace Substances Research Center in Columbia, Missouri.

Additional water samples were collected in hard glass bottles to measure conductivity, total dissolved solids, alkalinity, and pH. These analyses were conducted by the Cooperative Chemical Analytical Laboratory, Forestry Sciences Laboratory in Corvallis, Oregon. Total dissolved solids were determined using conductivity and a conversiton factor of 0.8.

Statistical Methods

Wet-weight concentrations of selenium and other trace elements, as reported by the laboratory, were converted to dry weights and presented as parts per million (ppm) unless otherwise noted. Values below detection limits (Appendix F) were assigned a value of 1/2 the lower limit of detection to eliminate values of zero for computational purposes. Residue concentrations were transformed to common logarithms for all statistical procedures to correct for skewed distributions (Sokal and Rohlf 1981). Geometric means (Sokal and Rohlf 1981) and ranges are reported for residue data. Frequency of occurrence of detectable concentrations was determined and differences were tested using a chi-square test of proportions (Sokal and Rohlf 1981). Significance between Kesterson and Volta means were examined with the Student's T-test procedure. Statistical differences by Student's T-test and chi-square test were judged significant at the 0.001 level to protect against inflation of the level of significance as a result of conducting numerous comparisons.

One-way analysis of variance (Snedecor and Cochran 1980) was used to determine whether there were significant differences among ponds or among seasons for trace element concentrations in water, sediment and biota samples. Student-Newman-Kuels Multiple Range test (Snedecor and Cochran 1980) was then used to separate means. A 3x2 or 2x2 factorial analysis of variance design was used to test for differences in selenium and boron concentrations in rhizomes, leaves, or seeds of plants collected at Kesterson. Bioaccumulation rates/factors were calculated for selenium and boron by dividing the concentrations present in the biota by the concentrations in water samples. Correlations of selenium and boron concentrations in water, sediments, submerged aquatic plants, and water boatmen (Corixidae) with water chemistry parameters were tested to examine relationships between contaminant concentrations and water chemistry (Appendix G). Simple correlations, analysis of variance, and multiple range tests were judged significant at the $P<0.05$ level.

RESULTS

Water Chemistry

Water quality at Kesterson and Volta differed considerably and varied with seasons (Table 4). Water at both Kesterson and Volta was alkaline with little difference in pH among seasons and ponds. However, alkalinity at Volta was about twice that at Kesterson and was inversely correlated ($r=-0.60$) with conductivity. The water at Kesterson, based on conductivity and total dissolved solids, was 4 to 13 times more saline than water at Volta, and salinity increased sequentially from ponds 2 to 11 for all seasons. Salinity at Kesterson also followed a seasonal pattern of minimum concentrations during May and maximum levels in August.

Selenium concentrations in water ($r=0.57$), sediments ($r=0.54$), widgeongrass ($r=0.82$), and water boatmen ($r=0.81$) were positively correlated with conductivity (Appendix G). Selenium concentrations in water, sediments, and widgeongrass were negatively correlated with alkalinity ($r=-0.79$, -0.52, -0.61, respectively). In contrast, boron concentrations in water ($r=0.90$) and water boatmen ($r=0.56$) were correlated with conductivity, and water and widgeongrass were negatively correlated with alkalinity ($r=-0.59$, -0.56, respectively).

Table 4: Water chemistry of ponds at Kesterson Reservoir and Volta Wildlife Management Area in May, August, and December, 1984.

	Volta	Kesterson		
	Pond 5	Pond 2	Pond 7	Pond 11
Alkalinity (ppm)				
May	294	172	157	198
August	306	165	173	228
December	367	177	148	164
Conductivity (mg/l)				
May	1122	7113	8017	10101
August	1462	14245	21786	24691
December	1646	11322	14122	15161
Total Dissolved Solids (mg/l)				
May	898	5690	6414	8081
August	1170	11396	17429	19753
December	1317	9058	11298	12129
pH				
May	8.4	7.8	8.9	8.8
August	7.8	8.1	8.2	7.7
December	8.6	8.3	8.3	8.3

Selenium

Abiotic samples-Selenium was not detected in water samples from Volta, while it was present in all samples from Kesterson (Table 5). The overall mean selenium concentration in water from Kesterson (mean=0.076 ppm, range=0.026-0.32 ppm) was 150 times greater than the lowest detectable level (Appendix F) at Volta (Table 6). Mean selenium concentration in sediments at Kesterson (mean=7.41 ppm, range=0.30-22 ppm) was significantly ($P<0.001$) higher than samples from Volta (mean=0.12 ppm, range=undetected-0.20 ppm).

Plants-Selenium was detected in all plant samples collected from Kesterson, while the frequency of detectable selenium concentrations in samples from Volta was much lower for most plants (Table 5). Mean selenium concentrations in aquatic plants, including algae and submergent and emergent macrophytes, collected from Kesterson were 85 to 290 times greater than samples from Volta (Table 6). Differences between means for all Kesterson and Volta samples (Table 6) and frequency of occurrence of detectable levels (Table 5) were significant ($P<0.001$).

Submerged rooted aquatic plants (i.e. widgeongrass) from Kesterson contained 20-310 ppm selenium (mean=74.1

Table 5. Frequency of occurrence (%) of detectable concentrations of trace elements in abiotic and biotic samples from Kesterson Reservoir and Volta Wildlife Management Area, 1984.

	Percent of Samples with Detectable Residues[b] (Sample Size)									
	Se	B	Cr	Mo	As	Cd	Cu	Pb	Hg	Ni
Water										
Kesterson	100(27)[a]	100(27)	67(27)	100(27)	100(27)	82(27)	96(27)	44(27)	96(26)	96(27)
Volta	0(8)	100(8)	25(8)	50(8)	100(8)	63(8)	63(8)	38(8)	38(8)	63(8)
Sediment										
Kesterson	100(27)	100(27)	100(27)	70(27)	100(27)	41(27)	100(27)	100(27)	63(27)	100(27)
Volta	56(9)	78(9)	100(9)	22(9)	100(9)	78(9)	100(9)	100(9)	100(9)	100(9)
Diatoms (*Nitzschia sigma*)										
Kesterson	100(24)	100(24)	--[c]	--	--	--	--	--	--	--
Volta	--	--	--	--	--	--	--	--	--	--
Algae (Filamentous Chlorophyta)										
Kesterson	100(9)	100(9)	78(9)	100(9)[a]	100(6)	--	--	--	--	--
Volta	50(6)	100(6)	100(6)	33(6)	100(3)	--	--	--	--	--
Submerged Aquatic Plants										
Kesterson	100(21)[a]	100(21)	62(21)	100(21)[a]	100(21)	29(21)	100(21)	100(21)	35(20)	95(21)
Volta	44(9)	100(9)	89(9)	22(9)	100(9)	78(9)	100(9)	100(9)	11(9)	89(9)
Submerged Aquatic Seeds										
Kesterson	100(12)	100(12)	--	--	--	--	--	--	--	--
Volta	67(3)	100(3)	--	--	--	--	--	--	--	--
Alkali Bulrush Rhizomes (*Scirpus maritimus*)										
Kesterson	100(12)	100(12)	--	--	--	--	--	--	--	--
Volta	83(6)	100(6)	--	--	--	--	--	--	--	--
Alkali Bulrush Seeds										
Kesterson	100(15)[a]	100(15)	--	--	--	--	--	--	--	--
Volta	0(6)	100(6)	--	--	--	--	--	--	--	--
Cattail Rhizomes (*Typha domingensis*)										
Kesterson	100(12)	100(12)	100(12)	100(12)[a]	--	--	--	--	--	--
Volta	67(6)	100(6)	100(6)	17(6)	--	--	--	--	--	--
Cattail Leaves										
Kesterson	100(12)[a]	100(12)	--	--	--	--	--	--	--	--
Volta	17(6)	100(6)	--	--	--	--	--	--	--	--
Cattail Seeds										
Kesterson	100(12)[a]	100(12)	--	--	--	--	--	--	--	--
Volta	33(6)	100(6)	--	--	--	--	--	--	--	--
Saltgrass Leaves (*Distichlis spicata*)										
Kesterson	100(27)	100(27)	--	--	--	--	--	--	--	--
Volta	78(9)	100(9)	--	--	--	--	--	--	--	--
Saltgrass Seeds										
Kesterson	100(8)	100(8)	--	--	--	--	--	--	--	--
Volta	67(3)	100(3)	--	--	--	--	--	--	--	--
Fathen Leaves (*Atriplex patula* var. hastata)										
Kesterson	100(27)	100(27)	33(27)	78(27)	--	--	--	--	--	--
Volta	50(6)	50(6)	50(6)	50(6)	--	--	--	--	--	--
Fathen Seeds										
Kesterson	100(9)	100(9)	--	--	--	--	--	--	--	--
Volta	--	--	--	--	--	--	--	--	--	--
Australian Saltbush Leaves (*Atriplex semibaccatta*)										
Kesterson	100(9)	--	--	--	--	--	--	--	--	--
Volta	33(3)	--	--	--	--	--	--	--	--	--

Table 5. Continued.

Australian Saltbush Seeds										
Kesterson	100(9)[a]	--	--	--	--	--	--	--	--	--
Volta	0(3)	--	--	--	--	--	--	--	--	--
Yellow Sweet-Clover Leaves (*Melitotus indica*)										
Kesterson	100(9)	100(9)	--	--	--	--	--	--	--	--
Volta	100(3)	100(3)	--	--	--	--	--	--	--	--
Yellow Sweet-Clover Seeds										
Kesterson	100(9)	100(9)	--	--	--	--	--	--	--	--
Volta	67(3)	100(3)	--	--	--	--	--	--	--	--
Brass Button Seeds (*Cotula cornopifola*)										
Kesterson	100(6)	100(6)	--	--	--	--	--	--	--	--
Volta	100(3)	100(3)	--	--	--	--	--	--	--	--
Fiddle Dock Seeds (*Rumex pulcher*)										
Kesterson	100(9)	100(9)	--	--	--	--	--	--	--	--
Volta	33(3)	100(3)	--	--	--	--	--	--	--	--
Cressa Leaves (*Cressa truxillensis*)										
Kesterson	100(6)	100(6)	--	--	--	--	--	--	--	--
Volta	100(3)	100(3)	--	--	--	--	--	--	--	--
Cressa Seeds										
Kesterson	100(9)	100(9)	--	--	--	--	--	--	--	--
Volta	100(3)	100(3)	--	--	--	--	--	--	--	--
Water Boatmen (Hemiptera)										
Kesterson	100(18)	100(17)	100(11)	64(11)	92(12)	100(11)	100(11)	100(11)	100(11)	64(11)
Volta	100(9)	100(9)	100(6)	83(6)	100(6)	100(6)	100(6)	100(6)	100(6)	100(6)
Damselfly Nymphs (Zygoptera)										
Kesterson	100(16)	94(16)	0(4)	0(3)	100(6)	100(3)	100(3)	67(3)	0(2)[a]	0(3)[a]
Volta	100(6)	100(6)	83(6)	33(6)	100(6)	100(6)	100(6)	100(6)	100(4)	83(6)
Dragonfly Nymphs (Anisoptera)										
Kesterson	100(14)	100(14)	--	--	--	--	--	--	--	--
Volta	100(6)	100(6)	--	--	--	--	--	--	--	--
Beetle Adults (Coleoptera)										
Kesterson	100(16)	100(16)	--	--	--	--	--	--	--	--
Volta	100(4)	100(4)	--	--	--	--	--	--	--	--
Fly Larvae (Diptera)										
Kesterson	100(23)	100(22)	--	--	--	--	--	--	--	--
Volta	100(9)	67(9)	--	--	--	--	--	--	--	--

[a]Kesterson and Volta samples significantly different by a chi-square test ($P<0.001$).
[b]Detectable levels are reported in Appendix F.
[c]Samples not analyzed for this element.

Table 6. Overall geometric mean selenium concentrations (ppm, dry weight/ except in water) and ranges in composite abiotic and biotic samples from Kesterson Reservoir and Volta Wildlife Management Area, 1984.

	Kesterson			Volta		
	N	Mean	(Range)	N	Mean	(Range)
Water	27	0.076	(0.026-0.32)	8	ND[b]	(ND)
Sediment[a]	27	7.41	(0.30-22)	9	0.12	(ND-0.20)
Diatoms	24	67.6	(26-220)		--[c]	
Filamentous Algae[a]	9	30.9	(14-120)	6	0.27	(ND-0.45)
Submerged Aquatic Plants	21	74.1	(20-310)	9	0.59	(ND-8.8)
Submerged Aquatic Seeds[a]	12	69.2	(15-240)	3	0.24	(ND-0.34)
Alkali Bulrush Rhizomes[a]	12	170	(100-280)	6	2.0	(ND-7.7)
Alkali Bulrush Seeds	15	5.62	(1.9-14)	6	ND	(ND)
Cattail Rhizomes[a]	12	141	(89-320)	6	0.60	(ND-1.2)
Cattail Leaves	12	37.2	(17-160)	6	0.15	(ND-0.43)
Cattail Seeds	12	13.2	(6.5-34)	6	0.14	(ND-0.46)
Saltgrass Leaves[a]	27	4.57	(0.5-27)	9	0.30	(ND-0.83)
Saltgrass Seeds[a]	8	3.63	(1.2-8.7)	3	0.13	(ND-0.30)
Fathen Leaves[a]	27	4.17	(1.7-9.5)	6	0.34	(ND-4.7)
Fathen Seeds	9	3.30	(1.4-5.6)		--	
Australian Saltbush Leaves[a]	9	1.91	(0.78-3.2)	3	0.085	(ND-0.13)
Australian Saltbush Seeds	9	0.55	(0.23-1.7)	3	ND	(ND)
Yellow Sweet-Clover Leaves[a]	9	1.66	(1.3-2.1)	3	0.35	(0.28-0.41)
Yellow Sweet-Clover Seeds[a]	9	1.48	(1.1-1.6)	3	0.13	(ND-0.22)
Brass Button Seeds[a]	6	2.57	(1.9-3.9)	3	0.65	(0.52-0.96)
Fiddle Dock Seeds[a]	9	6.03	(2.0-16)	3	0.087	(ND-0.13)
Alkali Weed Leaves[a]	6	3.39	(2.8-3.9)	3	1.38	(1.3-1.6)
Alkali Weed Seeds[a]	9	5.01	(0.92-65)	3	0.81	(0.38-1.2)
Water Boatmen[a]	18	18.6	(5.9-130)	9	1.62	(1.1-1.9)
Damselfly Nymphs[a]	16	97.7	(50-160)	6	1.51	(1.3-1.8)
Dragonfly Nymphs[a]	14	69.2	(48-110)	6	1.32	(1.0-1.7)
Beetle Adults[a]	16	58.9	(12-110)	4	2.10	(1.5-3.8)
Fly Larvae[a]	23	102	(76-180)	9	1.07	(0.5-1.8)

[a]Kesterson and Volta samples significantly different by Student's T-test (P<0.001).
[b]Not detected, see Appendix F.
[c]No samples collected.

ppm) (Table 6), and similar concentrations (mean=69.2 ppm, range=15-240 ppm) were found in widgeongrass seeds. Selenium concentrations in widgeon grass in August and December were significantly ($P<0.05$) higher than those in May, and widgeongrass seeds had significantly ($P<0.05$) higher concentrations in December than in August (Tables 7, 8). Filamentous green algae (Chlorophyta) ranged from 14-120 ppm (mean=30.9) (Table 6) and had slightly lower concentrations of selenium than widgeongrass. This group displayed similar seasonal patterns, with significantly ($P<0.05$) higher concentrations of selenium in December (Tables 7, 8). Diatoms (Nitzschia sigma) found only at Kesterson contained selenium concentrations of 26-220 ppm (mean=67.6 ppm) (Table 6). For most samples and seasons, pond 7 had the highest concentrations followed by pond 2 (Tables 7, 8). Mean selenium concentrations in algae and submerged aquatic plants and seeds from Volta were much lower and between 0.24 and 0.59 ppm (Table 6).

Selenium concentrations in cattails and alkali bulrush (Scirpus maritimus var. paludosus) from Kesterson varied with the plant part sampled. Rhizomes of cattails and alkali bulrush contained overall mean selenium concentrations of 141 ppm (range=89-320 ppm) and 170 ppm (range=100-280 ppm), respectively (Table 6). Concentrations in leaves and seeds were significantly

Table 7. Geometric mean selenium concentrations (ppm, dry weight/except in water) and ranges by season and pond at Kesterson Reservoir, 1984.

	Pond 2			Pond 7			Pond 11		
	May	August	December	May	August	December	May	August	December
Water	0.089 (0.073-0.12)	0.17 (0.12-0.32)	0.04 (0.037-0.061)	0.08 (0.061-0.086)	0.12 (0.11-0.14)	0.10 (0.056-0.14)	0.04 (0.035-0.04)	0.04 (0.026-0.052)	0.09 (0.085-0.010)
Sediment	18.2 (14-22)	9.3 (5.4-14)	9.3 (8.5-10)	0.76 (0.30-2.4)	5.9 (3.7-5.9)	11.2 (7.9-19)	11.5 (3.9-21)	15.9 (13-21)	4.4 (1.5-21)
Diatoms	38.0 (26-48)	52.5 (50-55)	58.9 (49-65)	200 (190-220)	79.4 (46-110)	87.1 (58-120)	--[a]	45.7 (42-50)	61.7 (61-64)
Widgeongrass	34.7 (27-44)	77.6 (73-85)	182 (131-284)	20.4 (20-22)	195 (190-200)	214 (130-310)	30.2 (25-34)	--	--
Widgeongrass Seeds	--	17.8 (15-24)	191 (160-240)	--	53.7 (51-56)	129 (120-150)	--	--	--
Alkali Bulrush Rhizomes	--	117 (100-150)	204 (180-250)	--	170 (150-200)	200 (140-280)	--	--	--
Alkali Bulrush Seeds	2.45 (1.9-2.9)	--	7.76 (7.4-8.3)	5.62 (3.8-8.0)	--	4.27 (3.5-4.9)	12.0 (10-14)	--	--
Cattail Rhizomes	--	97.7 (89-120)	110 (99-130)	--	282 (260-320)	126 (110-150)	--	--	--
Cattail Leaves	--	28.2 (27-28)	17.8 (17-19)	--	132 (100-160)	28.2 (21-40)	--	--	--
Cattail Seeds	--	15.9 (11-20)	7.59 (6.5-8.4)	--	21.4 (16-34)	11.5 (9.9-13)	--	--	--
Saltgrass Leaves	20.9 (14-27)	15.5 (13-20)	14.8 (14-16)	1.26 (1.1-1.4)	3.24 (2.9-3.8)	5.89 (3.2-10)	2.14 (2.0-2.3)	1.35 (0.5-2.7)	2.88 (2.7-3.0)
Fathen Leaves	3.98 (2.3-5.9)	8.51 (8.0-9.5)	4.47 (3.3-5.5)	2.00 (1.7-2.2)	5.13 (3.7-6.8)	4.27 (4.0-4.6)	5.13 (4.7-6.0)	5.37 (4.1-6.1)	2.04 (1.9-2.2)
Water Boatmen	(20)[b]	--	(10)[b]	(23)[b]	30.9 (28-32)	6.46 (5.7-7.5)	15.9 (13-20)	64.6 (34-130)	15.1 (14-16)
Damselfly Nymphs	138 (130-140)	93.3 (85-99)	--	91.2 (75-110)	69.2 (64-74)	--	64.6 (50-83)	148 (130-160)	--
Dragonfly Nymphs	(110)[b]	(65)[b]	--	61.7 (58-64)	56.2 (48-65)	--	63.1 (59-71)	95.5 (85-110)	--
Beetle Adults	(54)[b]	--	--	89.1 (86-95)	28.8 (12-61)	43.7 (28-73)	77.6 (54-110)	74.1 (68-79)	(110)[b]
Fly Larvae	117 (76-180)	93.3 (80-100)	105 (97-110)	95.5 (81-110)	97.7 (92-110)	102 (88-120)	--	126 (120-130)	85.1 (77-89)

[a]No samples collected.
[b]Only one sample collected.

Table 8. Ranking of the lowest to the highest selenium concentrations in samples by season and pond at Kesterson Reservoir, 1984.

Water	11M[a]	11A	2D	7M	2M	11D	7D	7A	2A[b]
Sediments	7M	11D	7A	2D	2A	7D	11M	11A	2M
Diatoms	2M	11A	2A	2D	11D	7A	7D	7M	
Widgeongrass	7M	11M	2M	2A	2D	7A	7D		
Widgeongrass Seeds	2A	7A	7D	2D					
Alkali Bulrush Rhizomes	2A	7A	7D	2D					
Alkali Bulrush Seeds	2M	7D	7M	2D	11M				
Cattail Rhizomes	2A	2D	7D	7A					
Cattail Leaves	2D	7D	2A	7A					
Cattail Seeds	2D	7D	2A	7A					
Saltgrass Leaves	7M	11A	11M	11D	7A	7D	2D	2A	2M
Fathen Leaves	7M	11D	2M	7D	2D	7A	11M	11A	2A
Water Boatmen	7D	2D	11D	11M	2M	7M	7A	11A	
Damselfly Nymphs	11M	7A	7M	2A	2M	11A			
Dragonfly Nymphs	7A	7M	11M	2A	11A	2M			
Beetle Adults	7A	7D	2M	11A	11M	7M	11D		
Fly Larvae	11D	2A	7M	7A	7D	2D	2M	11A	

[a]Identification codes: 2=Pond 2, 7=Pond 7, 11=Pond 11; M=May, A=August, D=December (e.g. 11M=Pond 11 in May).
[b]Significance between means is reported by the Student-Newman-Keuls Multiple Range test (P<0.05). Means that are not significantly different are underlined, and no underline in common indicates significance between those means.

lower ($P<0.05$). Cattail leaves contained 17-160 ppm (mean=37.2 ppm) selenium, and seeds had 6.5-34 ppm (mean=13.2 ppm). Overall mean selenium concentration (mean=5.6 ppm, range=1.9-14 ppm) in alkali bulrush seeds was considerably lower than in cattails. Selenium was not detectable in most Volta samples of cattails and alkali bulrush and ranged up to 2.0 ppm (Table 6). Detectable concentrations of selenium occurred in less than 35 percent of the alkali bulrush seeds and cattail leaves and seeds from Volta (Table 5). Concentrations in cattails at Kesterson decreased slightly from August to December, and concentrations found in pond 7 were slightly higher than pond 2 (Tables 7, 8). Selenium concentrations in alkali bulrush did not follow such a consistent pattern, but samples collected in December had greater concentrations than August for 2 of the 3 ponds.

Terrestrial plants at Kesterson (including fathen [*Atriplex patula* var. hastata], Australian saltbush [*Atriplex semibaccata*], saltgrass [*Distichlis spicata*], yellow sweet-clover [*Melilotus indica*], brass-buttons [*Cotula cornopifolia*], fiddle dock [*Rumex pulcher*], and alkali weed [*Cressa truxillensis* var. vallicola]) contained 2 to 70 times more selenium than the same species from Volta (Table 6). Selenium was detected in less than half of the samples of Australian saltbush leaves (33%) and seeds (0%), and fiddle dock seeds (33%) collected from Volta (Table 5). Leaf material from Kesterson contained 0.5-27 ppm (mean=3.5 ppm) selenium, and seeds averaged 2.5 ppm (range=0.23-65 ppm) (Table 6). Although the range in values was wide, mean selenium concentrations in most terrestrial plants from Kesterson were similar, generally from 1.48 to 6.03 ppm. Leaves of saltgrass and fathen, two of the most common species, contained mean selenium concentrations of 4.57 ppm and 4.17 ppm, respectively. Mean concentrations in terrestrial plants from Volta ranged from less than detectable levels (Appendix F) to 1.38 ppm (Table 6). Selenium concentrations in fathen leaves were slightly higher in August than other seasons, although these differences were not significant (Tables 7, 8). No apparent seasonal patterns occured in saltgrass, but pond 2 had significantly ($P<0.05$) higher concentrations than the other ponds. Saltgrass from pond 2 was collected near the water's edge and was subjected to periodic flooding while saltgrass was not collected as close to the water in the other ponds.

Selenium concentrations were different in various plant parts (Figure 4). Rhizomes of cattails and alkali bulrush from Kesterson had significantly ($P<0.001$) higher concentrations of selenium (141 and 170 ppm,

Figure 4. Overall geometric mean selenium concentrations (ppm, dry weight) in plant parts at Kesterson Reservoir in 1984.

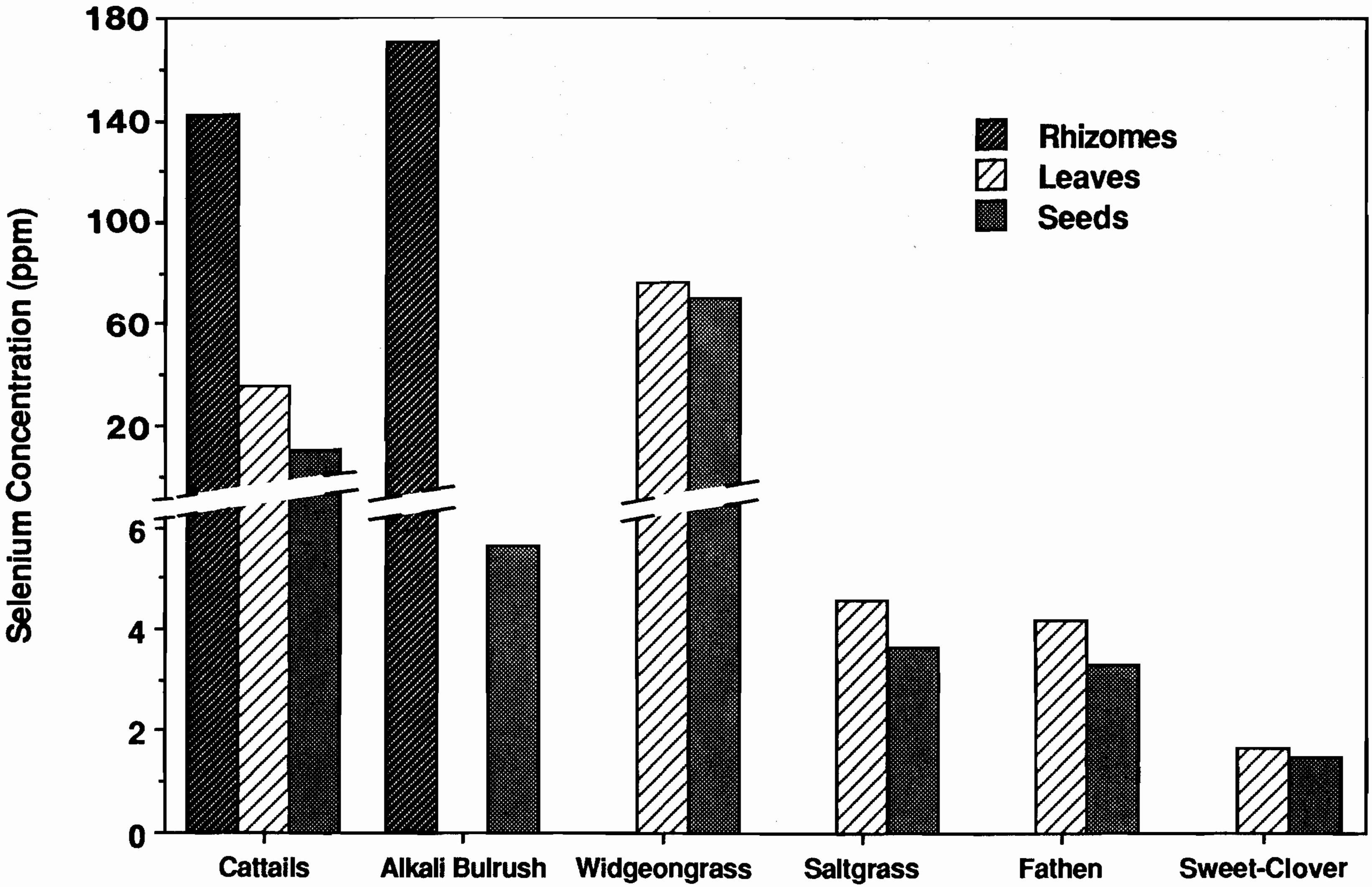

180
140
100
60
20
6
4
2
0
Selenium Concentration (ppm)
Rhizomes
Leaves
Seeds
Cattails
Alkali Bulrush
Widgeongrass
Saltgrass
Fathen
Sweet-Clover

Figure 4.

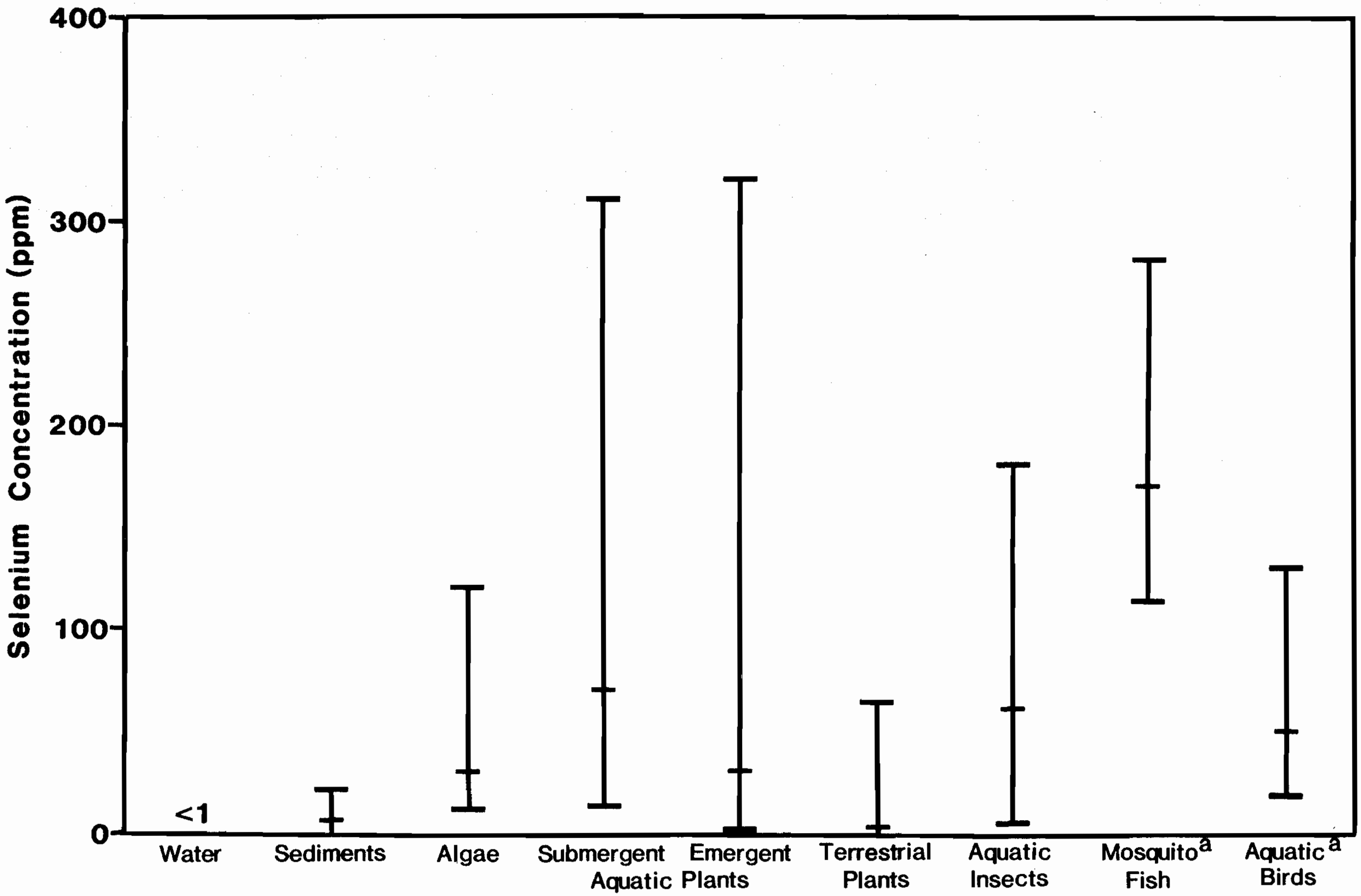
respectively) than concentrations in seeds and leaves of these species (cattail seeds=13.2 and leaves=37.2 ppm, alkali bulrush seeds=5.62 ppm). Furthermore, selenium concentrations in cattail leaves were higher than in seeds. Seeds and leaves of widgeongrass contained similar mean concentrations of 69.2 and 74.1 ppm selenium, respectively. Concentrations of selenium in leaves and seeds of terrestrial plants from Kesterson varied with the species. Although few differences were statistically significant, leaves commonly had higher concentrations.

Aquatic Insects-Damselfly nymphs (Zygoptera), dragonfly nymphs (Anisoptera), adult beetles (Coleoptera), fly larvae (Diptera), and water boatmen (Corixidae) were sampled. Selenium was detected in all samples of insects from both Kesterson and Volta (Table 5). However, mean selenium concentrations at Kesterson were 11 to 95 times greater than those from Volta (Table 6). Insects from Kesterson averaged 60.4 ppm selenium (range=5.9-180 ppm) and were significantly higher ($P<0.001$) than mean concentrations at Volta (mean=1.43, range=0.5-3.8 ppm). Water boatmen from Kesterson had considerably lower selenium concentrations than other insects (mean=18.6 ppm, range=5.9-130), but one composite sample from pond

11 in August contained 130 ppm. No other samples of water boatmen exceeded 32 ppm selenium. Mean selenium concentrations in other aquatic insects were between 58.9 and 102 ppm. Fly larvae from Kesterson had the highest mean selenium concentrations (102 ppm), followed by damselfy nymphs (97.7 ppm). For all insect groups, except water boatmen, pond 7 had slightly lower selenium concentrations than the other Kesterson ponds (Tables 7, 8). Water boatmen were the only insects to show a consistent seasonal pattern with a nominal increase in selenium concentrations in August.

Bioaccumulation-Selenium concentrations at Kesterson generally increased from water to sediments to aquatic plants, and from some of the plants (e.g. algae) to aquatic insects (Figure 5). Most biota at Kesterson bioaccumulated selenium to levels greater than 1000 times the concentration in water, and some more than 5000 times. Selenium bioaccumulated in aquatic plants 28 to 5100 (mean=1105) and in aquatic insects 168 to 3700 (mean=1090) times the concentration in water (Table 9). Most aquatic insects contained lower concentrations than rooted aquatic plants (e.g. widgeongrass, cattails), but higher concentrations than water, sediments, algae, and diatoms (Figure 5).

Figure 5. Comparisons of minimum, maximum, and geometric mean selenium concentrations (ppm, dry weight/ except in water) in the food chain at Kesterson Reservoir, 1984.



[a]Ohlendorf et al 1986a

Figure 5.

Table 9. Bioaccumulation rates/factors of selenium in sediments and biota from Kesterson Reservoir, 1984.

	Pond 2			Pond 7			Pond 11		
	May	Aug	Dec	May	Aug	Dec	May	Aug	Dec
Sediments	204[a]	55	233	9.5	49	112	288	398	49
Diatoms	427	309	1473	2500	662	871	--[b]	1143	686
Widgeongrass	390	456	4550	255	1625	2140	755	--	--
Widgeongrass Seeds	--	105	4775	--	448	1290	--	--	--
Alkali Bulrush Rhizomes	--	688	5100	--	1417	2000	--	--	--
Alkali Bulrush Seeds	28	--	194	70	--	43	300	--	--
Cattail Rhizomes	--	575	2750	--	2350	1260	--	--	--
Cattail Leaves	--	166	445	--	1100	282	--	--	--
Cattail Seeds	--	94	190	--	178	115	--	--	--
Water Boatmen	219	--	255	286	258	65	398	1615	168
Damselfly Nymphs	1551	549	--	1138	577	--	1615	3700	--
Dragonfly Nymphs	1202	380	--	771	468	--	1578	2388	--
Beetle Adults	603	--	--	1114	240	437	1940	1853	1167
Fly Larvae	1315	549	2625	1194	814	1020	--	--	--

Mean in Sediments = 155
Mean in Aquatic Plants = 1105 (Submergent plants=1308; Emergent plants=921)
Mean in Aquatic Insects = 1090

[a]Bioaccumulation rates were calculated by dividing the concentration present in biota by the concentrations in water samples collected at the same sites and times.
[b]No samples collected.

Boron

Abiotic Samples-Boron was detected in all water and sediment samples from Kesterson, and in 100 percent of water and 77.8 percent of sediment samples from Volta (Table 5). Overall mean boron concentration in water from Kesterson was 11 times greater than that from Volta (Table 10). Water samples from Kesterson contained a significantly ($P<0.001$) higher mean boron concentration (mean=20 ppm, range=12-41 ppm) than Volta (mean=1.82 ppm, range=1.4-2.2 ppm). Mean boron concentrations in sediments from Kesterson and Volta were not significantly ($P<0.001$) different, probably due to the high sample variability (Table 10).

Plants-Boron was detected in all plant samples from both Kesterson and Volta, with the exception of fathen leaves from Volta (50% occurrence) (Table 5). Significantly ($P<0.001$) higher mean concentrations of boron occurred in algae and submerged rooted aquatic plants and seeds (i.e. widgeongrass) from Kesterson as compared to similar samples from Volta (Table 10). Widgeongrass from Kesterson contained 120-780 ppm boron (mean=371 ppm), and considerably higher concentrations of 450-3500 ppm (mean=1860 ppm) were found in widgeongrass seeds. Diatoms from Kesterson contained 230-630 ppm boron

Table 10. Overall geometric mean boron concentrations (ppm, dry weight/except in water) and ranges in composite abiotic and biotic samples from Kesterson Reservoir and Volta Wildlife Management Area, 1984.

	Kesterson			Volta		
	N	Mean	(Range)	N	Mean	(Range)
Water[a]	27	20.0	(12-41)	8	1.82	(1.4-2.2)
Sediment	27	20.0	(10-71)	9	10.0	(ND[b]-25)
Diatoms	24	324	(230-630)		--[c]	
Filamentous Algae[a]	9	501	(390-787)	6	85.1	(64-140)
Submerged Aq. Plants[a]	21	371	(120-780)	9	100	(37-540)
Submerged Aq. Seeds[a]	12	1860	(450-3500)	3	35.5	(32-43)
Alkali Bulrush Rhizomes	12	316	(190-470)	6	170	(33-640)
Alkali Bulrush Seeds	15	39.8	(25-63)	6	45.7	(17-122)
Cattail Rhizomes[a]	12	275	(220-320)	6	110	(88-170)
Cattail Leaves	12	178	(35-960)	6	34.7	(14-130)
Cattail Seeds	12	38.9	(21-41)	6	31.6	(24-71)
Saltgrass Leaves	27	74.1	(20-339)	9	74.1	(20-220)
Saltgrass Seeds	8	148	(110-240)	3	87.1	(75-100)
Fathen Leaves	27	229	(120-620)	6	138	(28-750)
Fathen Seeds	9	56.2	(39-73)		--	
Yellow-sweet Clover Lvs.	9	186	(110-330)	3	95.5	(70-170)
Yellow-sweet Clover Sds.[a]	9	42.7	(33-50)	3	28.2	(27-29)
Brass Button Seeds[a]	6	107	(86-140)	3	51.3	(47-58)
Fiddle Dock Seeds[a]	9	61.7	(44-88)	3	28.2	(23-37)
Alkali Weed Leaves	6	490	(280-870)	3	427	(420-430)
Alkali Weed Seeds	9	146	(60-260)	3	427	(410-440)
Waterboatmen[a]	17	42.6	(22-120)	9	11.8	(7.4-21)
Damselfly Nymphs	16	93.3	(ND-320)	6	26.3	(14-49)
Dragonfly Nymphs[a]	14	186	(78-340)	6	28.8	(21-38)
Beetle Adults[a]	16	110	(63-180)	4	31.6	(20-47)
Fly Larvae	22	33.9	(4.1-140)	9	11.5	(ND-55)

[a]Kesterson and Volta samples significantly different by Student's T-test ($P<0.001$).
[b]Not detected, see Appendix F.
[c]No samples collected.

(mean=324 ppm), and algae contained boron concentrations of 390-790 ppm (mean=501 ppm). Mean boron concentrations in algae and submerged aquatic plants and seeds from Volta were between 35.5 and 100 ppm. A significantly ($P<0.001$) higher concentration of boron was found in diatoms from pond 11 and widgeongrass seeds from pond 7 at Kesterson, and concentrations of boron were higher in December than in other months for some submerged plants (Tables 11, 12).

Emergent aquatic plants from Kesterson had significantly ($P<0.05$) higher boron concentrations than Volta, except for alkali bulrush seeds, which had slightly higher levels in samples from Volta (Table 10). Rhizomes of cattails and alkali bulrush contained mean boron concentrations of 294 ppm (range=190-470 ppm), while concentrations found in leaves and seeds were much lower. Cattail leaves contained 35-960 ppm boron (mean=178 ppm), and cattail and alkali bulrush seeds contained 21-63 ppm (mean=39.3 ppm). Mean boron concentrations in emergent aquatic plants from Volta ranged from 31.6 to 170 ppm. Higher boron concentrations occurred in alkali bulrush seeds and rhizomes and cattail seeds from Kesterson in December, and cattail rhizomes and leaves had higher concentrations in August (Table 11, 12).

Table 11. Geometric mean boron concentrations (ppm, dry weight/except in water) and ranges by season and pond at Kesterson Reservoir, 1984.

	Pond 2			Pond 7			Pond 11		
	May	August	December	May	August	December	May	August	December
Water	15.9 (16-16)	16.2 (16-17)	12.3 (12-13)	19.1 (19-19)	25.7 (24-26)	22.9 (22-24)	20.9 (20-21)	40.7 (40-41)	15.1 (14-16)
Sediments	26.3 (23-30)	10.0 (10-10)	11.5 (10-15)	21.4 (16-31)	20.9 (18-25)	13.5 (10-16)	46.8 (23-71)	26.9 (22-33)	23.4 (10-57)
Diatoms	257 (240-270)	234 (230-250)	251 (230-280)	339 (320-360)	295 (240-400)	324 (320-330)	--[a]	468 (350-550)	575 (550-630)
Widgeongrass	182 (120-330)	468 (460-480)	347 (300-430)	363 (350-390)	275 (190-470)	708 (630-780)	468 (450-500)	--	--
Widgeongrass Seeds	--	537 (450-610)	2400 (2300-2500)	--	2690 (2600-2800)	3390 (3300-3500)	--	--	--
Alkali Bulrush Rhizomes	--	214 (190-230)	398 (370-470)	--	282 (270-280)	417 (380-440)	--	--	--
Alkali Bulrush Seeds	27.5 (25-33)	--	63.1 (54-63)	38.0 (35-39)	--	38.0 (34-44)	38.9 (35-43)	--	--
Cattail Rhizomes	--	288 (270-300)	229 (220-240)	--	309 (300-320)	282 (260-300)	--	--	--
Cattail Leaves	--	759 (630-960)	43.7 (35-52)	--	631 (420-800)	45.7 (40-50)	--	--	--
Cattail Seeds	--	29.5 (24-34)	43.7 (36-52)	--	30.9 (28-39)	56.2 (37-71)	--	--	--
Saltgrass Leaves	110 (75-160)	263 (230-310)	31.6 (28-33)	81.3 (81-82)	74.1 (69-86)	26.9 (26-84)	79.4 (67-89)	257 (197-339)	21.9 (20-25)
Fathen Leaves	186 (160-210)	457 (420-500)	245 (230-370)	162 (150-170)	490 (380-620)	144 (120-190)	170 (150-200)	263 (250-270)	170 (150-190)
Water Boatmen	--	--	(27.9)	38.0 (28-55)	77.6 (54-120)	29.5 (22-35)	93.3 (75-110)	46.8 (40-55)	24.0 (22-29)
Damselfly Nymphs	91.2 (74-110)	110 (82-150)	--	77.6 (75-80)	186 (130-320)	--	27.5 (NDb-220)	112 (100-120)	--
Dragonfly Nymphs	(78)	(97)	--	174 (170-190)	251 (240-260)	--	151 (130-170)	302 (280-340)	--
Beetle Adults	(93)	--	--	123 (100-170)	112 (63-180)	112 (100-120)	120 (99-150)	105 (97-120)	(92)
Fly Larvae	--	13.2 (6.5-19)	9.33 (6.3-13)	67.6 (53-96)	32.4 (4.1-110)	37.2 (25-58)	--	115 (100-140)	41.7 (31-49)

[a] No samples collected.
[b] Not detected, see Appendix F.

Table 12. Ranking of the lowest to the highest boron concentrations in samples by season and pond at Kesterson Reservoir, 1984.

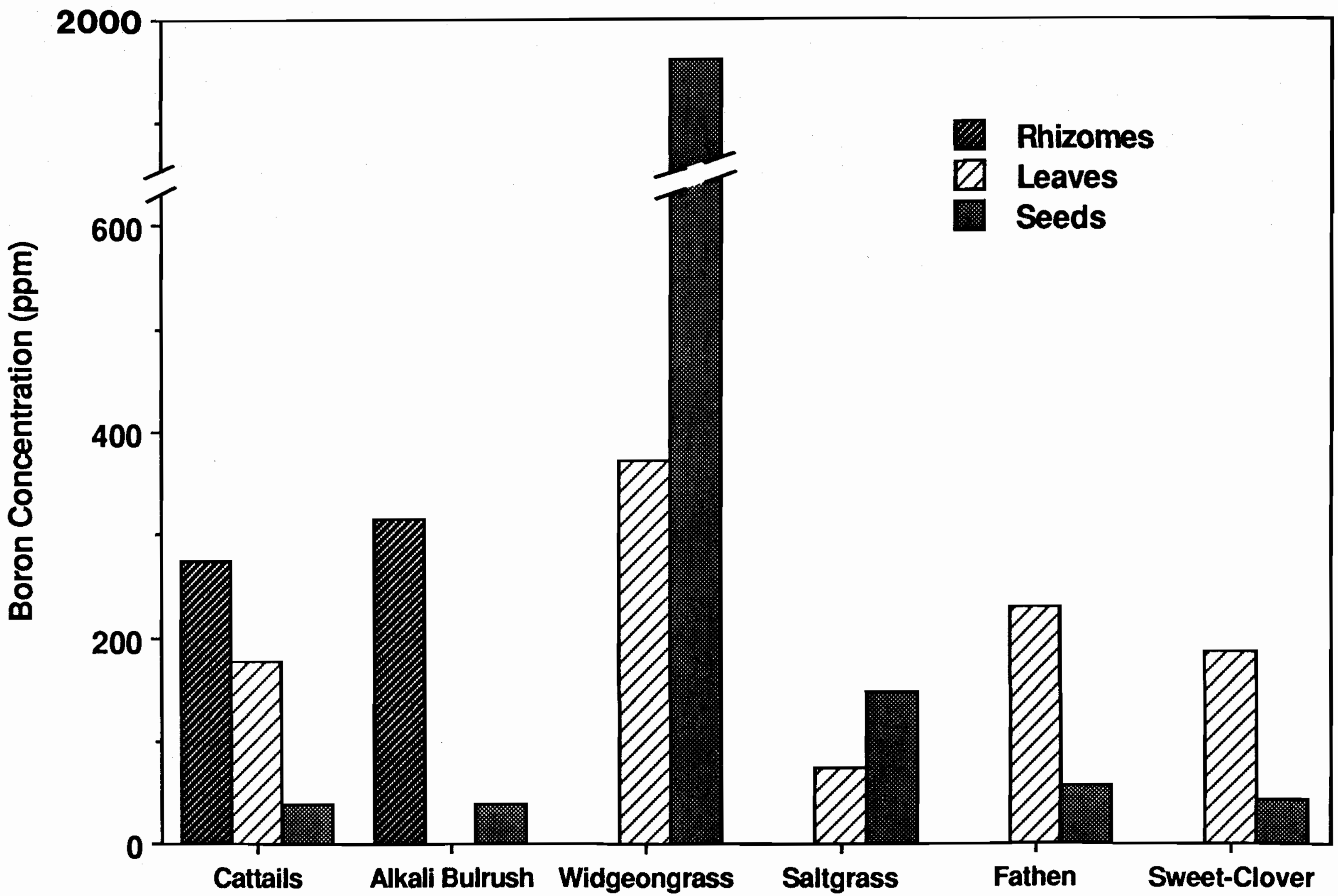
Water	2D[a]	11D	2M	2A	7M	11M	7D	7A	11A
Sediments	2A	2D	7D	7A	7M	11D	2M	11A	11M[b]
Diatoms	2A	2D	2M	7A	7D	7M	11A	11D	
Widgeongrass	2M	7A	2D	7M	2A	11M	7D		
Widgeongrass Seeds	2A	2D	7A	7D					
Alkali Bulrush Rhizomes	2A	7A	2D	7D					
Alkali Bulrush Seeds	2M	7M	7D	11M	2D				
Cattail Rhizomes	2D	7D	2A	7A					
Cattail Leaves	2D	7D	7A	2A					
Cattail Seeds	2A	7A	2D	7D					
Saltgrass Leaves	11D	7D	2D	7A	11M	7M	2M	11A	2A
Fathen Leaves	7D	7M	11M	11D	2M	2D	11A	2A	7A
Water Boatmen	2M	11D	2D	7D	7M	11A	7A	11M	
Damselfly Nymphs	11M	7M	2M	2A	11A	7A			
Dragonfly Nymphs	2M	2A	11M	7M	7A	11A			
Beetle Adults	2M	11D	11A	7A	7D	11M	7M		
Fly Larvae	2M	2D	2A	7A	7D	11D	7M	11A	

[a]Identification codes: 2=Pond 2, 7=Pond 7, 11=Pond 11; M=May, A=August, D=December (e.g. 2D=Pond 2 in December).
[b]Significance between means is reported by the Student-Newman-Keuls Multiple Range test (P<0.05). Means that are not significantly different are underlined, and no underline in common indicates significance between those means.

Boron concentrations in most terrestrial plants were greater at Kesterson than Volta, although few differences were significant ($P<0.001$) (Table 10). Boron concentrations in leaf materials at Kesterson were 20 to 870 ppm (mean=245 ppm), and those in seeds were 33 to 260 ppm (mean=93.6 ppm). In comparison, mean concentrations in samples from Volta ranged from 28.2 to 427 ppm. August samples of fathen and saltgrass from Kesterson contained significantly ($P<0.05$) higher boron concentrations than those from other seasons (Tables 11, 12).

As with selenium, boron concentrations in plant parts differed significantly ($P<0.05$) (Figure 6). Widgeongrass seeds (1860 ppm) from Kesterson had 5 times the average concentrations found in leaves (371 ppm). Cattails and alkali bulrush had the highest concentrations of boron in rhizomes (275 and 316 ppm, respectively), followed by leaves (cattail 178 ppm) and seeds (cattail 38.9 ppm; alkali bulrush 39.8 ppm). Concentrations found in leaves and seeds of terrestrial plants varied with the species examined, although the highest boron concentrations were in leaves of most species.

Figure 6. Overall geometric mean boron concentrations (ppm, dry weight) in plant parts at Kesterson Reservoir, 1984.



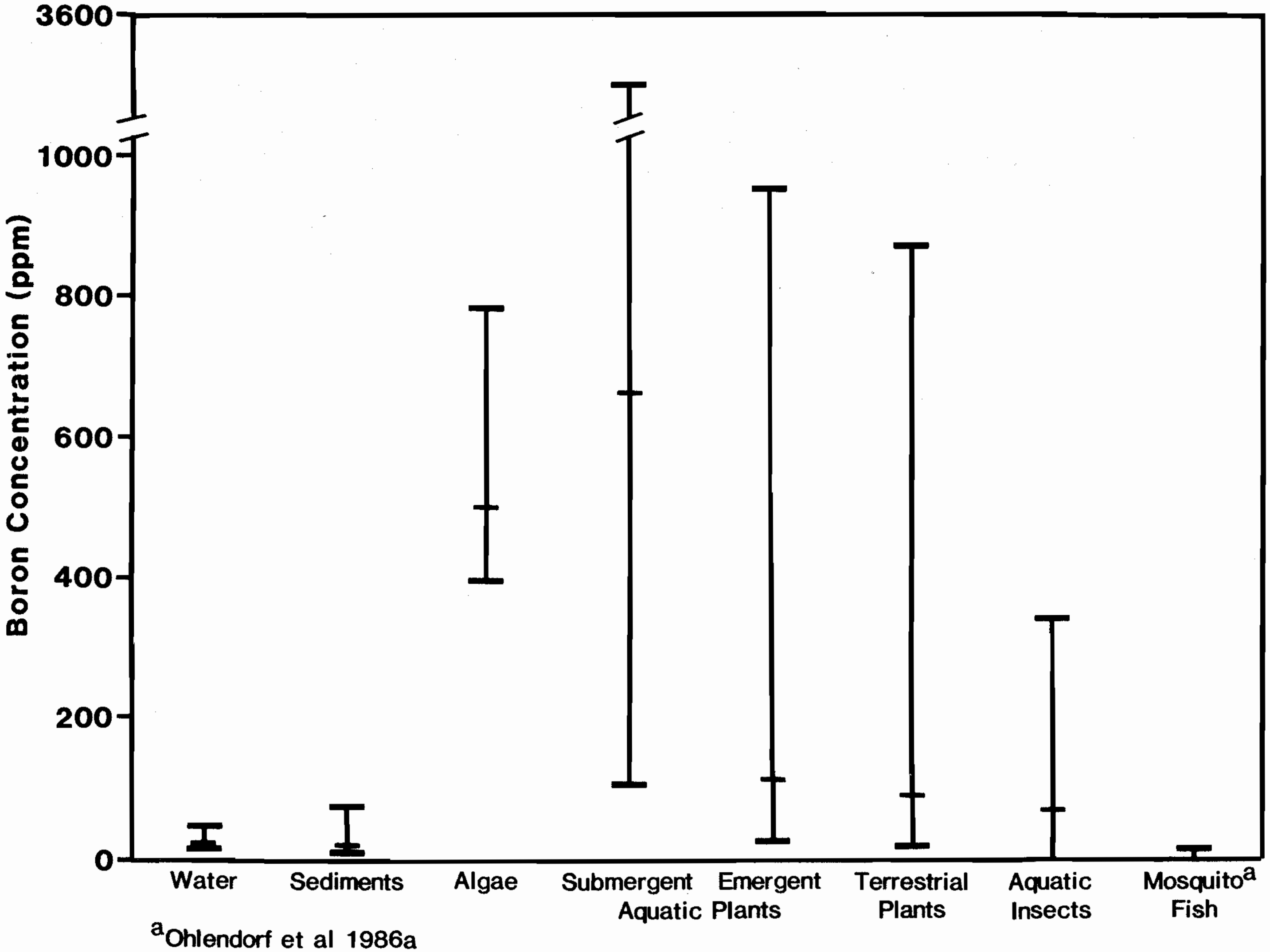
2000
600
400
200
0
Boron Concentration (ppm)
Rhizomes
Leaves
Seeds
Cattails
Alkali Bulrush
Widgeongrass
Saltgrass
Fathen
Sweet-Clover

Figure 6.

Aquatic Insects-Boron was detected in all aquatic insect samples from Kesterson and Volta except for damselfy nymphs (94%) at Kesterson and fly larvae (67%) at Volta (Table 5). Insects from Kesterson had an overall mean boron concentration of 93.2 ppm (range=undetected-340 ppm), as compared to 17.7 ppm (range=undetected-5 ppm) for insects from Volta (Table 10). All insects from Kesterson had higher mean boron concentrations than found at Volta, but only water boatmen, dragonfly nymphs, and beetle adults were significantly ($P<0.001$) higher. Highest boron concentrations were found in adult beetles and damselfly and dragonfly nymphs (means=110, 93.3, and 186 ppm, respectively), with the latter two groups having composite samples exceeding 300 ppm. Damselfly and dragonfly nymphs from Kesterson showed a substantial increase in boron concentrations from May to August (Tables 11, 12). Other insects did not have clear seasonal patterns, although beetles did have slightly higher concentrations in May.

Bioaccumulation-Aquatic plants and insects at Kesterson accumulated boron at higher concentrations than levels in water and sediments, but aquatic insects concentrated boron at lower levels than plants (Figure 7). Boron bioaccumulated in aquatic plants 1.2 to 195 (mean=25) and

Figure 7. Comparisons of minimum, maximum, and geometric mean boron concentrations (ppm, dry weight/ except in water) in the food chain at Kesterson Reservoir, 1984.



3600
1000
800
600
400
200
0
Boron Concentration (ppm)
Water
Sediments
Algae
Submergent Aquatic Plants
Emergent Aquatic Plants
Terrestrial Plants
Aquatic Insects
Mosquito[a] Fish
[a]Ohlendorf et al 1986a

Figure 7.

most aquatic insects 1.2 to 10 (mean=4) times the concentration in water, with the highest bioaccumulation rates occurring in widgeongrass seeds (mean=121) (Table 13).

Heavy Metals

Concentrations of arsenic, cadmium, chromium, copper, lead, mercury, molybdenum, and nickel are reported in Table 14. Most biotic samples had slightly higher metal concentrations at Volta, with the exception of molybdenum. Molybdenum was consistently higher at Kesterson, although differences were not significant at the 0.001 level. In contrast, metal concentrations in water samples were higher at Kesterson than at Volta. Concentrations in sediment samples followed similar patterns as the biota with all metals, except molybdenum, having higher concentrations at Volta. Arsenic, chromium, copper, lead, and nickel were significantly ($P<0.001$) higher at Volta in sediments and biota than at Kesterson.

Overall mean chromium concentrations in the biota from Volta were 2 to 25 times greater than those at Kesterson, and composite samples of algae, cattail rhizomes, and water boatmen from Volta had significantly ($P<0.001$) higher concentrations (Table 14). Mean

Table 13. Bioaccumulation rates/factors of boron in sediments and biota from Kesterson Reservoir, 1984.

	Pond 2			Pond 7			Pond 11		
	May	Aug	Dec	May	Aug	Dec	May	Aug	Dec
Sediments	2[a]	0.6	0.9	1.1	0.8	0.6	2	0.7	1.6
Diatoms	16	14	20	18	11	14	--[b]	12	38
Widgeongrass	11	29	28	19	11	31	22	--	--
Widgeongrass Seeds	--	33	195	--	105	148	--	--	--
Alkali Bulrush Rhizomes	--	13	32	--	11	18	--	--	--
Alkali Bulrush Seeds	2	--	5	2	--	2	2	--	--
Cattail Rhizomes	--	18	19	--	12	12	--	--	--
Cattail Leaves	--	47	4	--	25	2	--	--	--
Cattail Seeds	--	2	4	--	1.2	2	--	--	--
Water Boatmen	--	--	2	2	3	1.2	4	1.2	1.6
Damselfly Nymphs	6	7	--	4	7	--	1.2	3	--
Dragonfly Nymphs	5	6	--	9	10	--	7	7	--
Beetle Adults	6	--	--	6	4	5	6	3	6
Fly Larvae	--	0.8	0.8	4	1.3	1.6	--	3	3

Mean in Sediments = 1.1
Mean in Aquatic Plants = 25 (Submergent plants=41; Emergent plants=11)
Mean in Aquatic Insects = 4

[a]Bioaccumulation factors were calculated by dividing the concentration present in biota by the concentrations in water samples collected at the same sites and times.
[b]No samples collected.

Table 14. Overall geometric mean concentrations and ranges of trace elements (ppm, dry weight/except in water) in composite abiotic and biotic samples from Kesterson Reservoir and Volta Wildlife Management Area, 1984.

	Mean (Range)							
	Arsenic		Cadmium		Chromium		Copper	
Water								
Kesterson	0.001[a]	(0.0007-0.0042)	0.0009	(ND[b]-0.0077)	0.0040	(ND-0.032)	0.011	(ND-0.064)
Volta	0.0047	(0.0020-0.010)	0.0007	(ND-0.010)	0.0010	(ND-0.010)	0.0020	(ND-0.014)
Sediments								
Kesterson	0.93[a]	(0.40-3.1)	0.037	(ND-0.10)	15.9[a]	(10-27)	8.13[a]	(4.6-16)
Volta	3.13	(1.7-8.5)	0.089	(ND-0.24)	63.1	(57-82)	26.9	(17-34)
Filamentous Algae								
Kesterson	--[c]		--		1.17[a]	(ND-4.4)	--	
Volta	--		--		29.5	(12-68)	--	
Submerged Aquatic Plants								
Kesterson	2.34	(0.59-18)	0.0388	(ND-0.85)	3.13	(ND-10)	2.93	(3.0-11)
Volta	3.80	(1.3-8.2)	0.17	(ND-0.63)	5.13	(ND-25)	8.32	(4.0-14)
Cattail Rhizomes								
Kesterson	--		--		3.89[a]	(2.1-8.5)	--	
Volta	--		--		28.2	(15-52)	--	
Fathen Leaves								
Kesterson	--		--		0.57	(ND-3.1)	--	
Volta	--		--		0.89	(ND-3.7)	--	
Water Boatmen								
Kesterson	0.35	(ND-0.86)	0.31	(0.08-0.74)	0.68[a]	(0.32-1.0)	16.6	(12-22)
Volta	0.79	(0.30-2.0)	0.91	(0.63-1.3)	3.02	(1.5-6.9)	27.5	(18-40)
Damselfly Nymphs								
Kesterson	1.17	(0.68-3.9)	0.22	(0.18-0.25)	ND	(ND-ND)	12.0	(11-13)
Volta	2.57	(1.7-3.5)	0.59	(0.31-0.84)	1.74	(ND-7.7)	13.2	(10-15)

Table 14. Continued.

	Mean (Range)			
	Lead	Mercury	Molybdenum	Nickel
Water				
Kesterson	0.0021 (ND-0.037)	0.0002 (ND-0.0012)	0.017[a] (0.069-0.29)	0.048[a] (ND-0.15)
Volta	0.0007 (ND-0.0022)	0.0003 (ND-0.0019)	0.005 (ND-0.019)	0.0042 (ND-0.0094)
Sediments				
Kesterson	5.62[a] (3.5-21)	0.19 (ND-12)	0.50 (ND-5.0)	21.4[a] (13-36)
Volta	9.77 (7.9-13)	0.43 (0.080-11)	0.19 (ND-0.93)	87.1 (72-110)
Filamentous Algae				
Kesterson	--	--	2.63 (0.59-5.7)	--
Volta	--	--	0.98 (ND-4.4)	--
Submerged Aquatic Plants				
Kesterson	0.604 (0.37-2.7)	0.21 (ND-3.4)	0.802 (1.7-12)	2.61 (ND-9.5)
Volta	2.82 (0.13-16)	0.11 (ND-0.25)	0.68 (ND-2.6)	6.17 (ND-26)
Cattail Rhizomes				
Kesterson	--	--	9.12 (3.5-18)	--
Volta	--	--	0.74 (ND-1.9)	--
Fathen Leaves				
Kesterson	--	--	1.23 (ND-5.2)	--
Volta	--	--	0.66 (ND-26)	--
Water Boatmen				
Kesterson	0.39 (0.19-0.74)	0.35 (0.21-0.52)	0.52 (ND-1.6)	0.65 (ND-3.1)
Volta	0.76 (0.63-0.89)	0.37 (0.33-0.42)	0.89 (ND-1.7)	2.14 (0.74-5.9)
Damselfly Nymphs				
Kesterson	0.34 (ND-1.2)	ND (ND-ND)	0.38 (ND-0.60)	ND (ND-ND)
Volta	1.07 (0.39-1.9)	0.35 (0.31-0.42)	0.48 (ND-1.2)	2.51 (ND-7.1)

[a]Kesterson and Volta samples significantly different by Student's T-test (P<0.001).
[b]Not detected, see Appendix F.
[c]Samples not analyzed for this element.

chromium concentrations in biotic samples from Volta ranged from 0.89 to 29.5 ppm (Table 14), while samples from Kesterson contained average concentrations between less than the detectable level (Appendix F) and 3.9 ppm (Table 14).

Molybdenum was the only trace element besides selenium and boron that was usually higher at Kesterson, although the only significant ($P<0.001$) difference occurred in water (Table 14). Most abiotic and biotic components from Volta had less than 50 percent of the samples with detectable levels of molybdenum. Frequency of occurrence of molybdenum at Kesterson was significantly ($P<0.001$) greater for algae, submerged aquatic plants, and cattail rhizomes than at Volta (Table 5). Mean molybdenum concentrations at Kesterson ranged from 0.017 to 9.12 ppm while levels at Volta were between 0.005 and 0.98 ppm (Table 14). Overall mean molybdenum concentrations in plant samples from Kesterson were 1.2 to 12 times greater than those from Volta. In contrast to water, sediments, and plants, molybdenum concentrations in aquatic insects at Kesterson were slightly lower than those from Volta.

No significant differences ($P>0.001$) were observed in the other metals for any of the biotic samples (Table 14), and less than 50 percent of the samples had detectable levels for many of the metals from both areas (Table 5).

DISCUSSION

Selenium

Aquatic biota at Kesterson contained considerably higher concentrations of selenium than at Volta. Concentrations in some aquatic plants and insects exceeded 300 and 180 ppm selenium, respectively. Aquatic plants at Kesterson contained up to 64 times the selenium concentration (5 ppm) reported to reduce reproductive success of birds (Arnold et al. 1973, El-Begearmi et al. 1977, Ort and Latshaw 1978). These high concentrations in the food chain were the most likely cause of reproductive problems observed in aquatic birds by Ohlendorf et al. (1986a, 1986b), and consumption of aquatic plants and insects at Kesterson was undoubtedly the primary source of selenium in bird tissues.

Concentrations of selenium in the Kesterson ecosystem in this study were comparable to those found in studies at Kesterson in 1983 (Ohlendorf et al. 1986a; Saiki 1986a, 1986b), but there were some differences. Of the samples collected, filamentous algae (Saiki 1986a, 1986b), aquatic insects (Ohlendorf et al 1986a; Saiki 1986a, 1986b), and sediments (Saiki 1986a, 1986b) had higher selenium concentrations in 1983 than those in 1984. Filamentous algae (this study) had higher concentrations (14-120 ppm) than reported by Ohlendorf et al. (1986a) (12-68 ppm), but lower (12-330 ppm) than reported by Saiki (1986a, 1986b). Aquatic insects had a maximum concentration of 320 ppm selenium (Saiki 1986a, 1986b) in 1983, higher than the 200 ppm in this study. Mean selenium concentration in sediments from 1983 was 16 ppm, while sediments contained a mean concentration of 7.4 ppm in 1984. These differences do not show increasing selenium concentrations in the biota over time. Concentrations in most samples were generally similar from 1983 to 1984, and the differences observed may be attributed to variations in laboratory analysis, season, pond, and species sampled, as well as specific sample collection sites within individual ponds.

Accumulation of selenium in the biota depends on many factors including species, season, location, environmental factors, chemical form of selenium, and stage of physiological development (Rosenfeld and Beath 1964, Bisbjerg and Gissel-Nielsen 1969, Lakin 1973, Wells et al. 1980, Brown and Shrift 1982). Seasonal variations in selenium concentrations were observed in some aquatic plants, but few consistent patterns were observed in aquatic insects. Saiki (1986b) observed an increase in selenium in aquatic insects from May to August of 1983, but that pattern was not as evident in this study. The only consistent seasonal pattern occurred in water boatmen, which showed an increase in selenium from May to August and a decrease in December. In contrast, many plants showed seasonal variations in selenium concentrations. The highest concentrations usually occur in spring and summer when vegetative growth is most active, and lower levels occurred in fall and winter when growth declines (Beath et al. 1937, Moxon et al. 1950, Rosenfeld and Beath 1964). This general pattern was observed in this study in some terrestrial and aquatic plants (e.g. above ground section of cattails) that were viable in summer and died off by December. These plants had highest selenium concentrations in August and lower concentrations in December. Saiki (1986b) also found that selenium concentrations in aquatic plants increased from spring to summer in 1983 at Kesterson. In 1984, aquatic plants and/or plant parts (i.e. widgeongrass, cattail rhizomes, alkali bulrush rhizomes) that remained viable throughout the year, usually showed a steady selenium increase from May to August to December. Some of these plants are an important food source to wintering waterfowl (Appendix B, Connelly and Chesmore 1980, Euliss 1984), and they contained some of the highest selenium concentrations in the food chain.

Because subsurface drainwater entered Kesterson at

Pond 2 and flowed north to ponds 7 and 11, the accumulation of selenium would be expected to depend upon the rate of removal of selenium from the water. Thus, there was a potential for differences in selenium concentrations among ponds. Saiki (1986b) reported that aquatic plants in ponds 2 and 8 had the highest selenium concentrations, with concentrations decreasing as water flowed northward in the pond sequence. This pattern was also observed for some species in this study (using pond 7 instead of 8); however, there were many exceptions and variations appeared to be greatly influenced by species and season of collections.

The distribution of selenium in plants is usually not uniform in any one part during a growing season (Beath et al. 1937, Rosenfeld and Beath 1964, Johnson et al. 1967, Gissel-Nielsen 1971). Selenium accumulation in plant parts at Kesterson varied with the species and season sampled, but some trends did occur. Rhizomes of aquatic emergent plants (i.e. cattail and alkali bulrush) contained higher selenium concentrations than leaves, and leaves had higher concentrations than seeds. Leaves and seeds of submergent aquatic species (i.e. widgeongrass) had similar selenium concentrations and leaves of terrestrial plants commonly had higher concentrations than seeds. Some authors have noted similar patterns as observed in this study (Hamilton and Beath 1964, Bisbjerg and Gissel-Nielsen 1969), while others have reported entirely different trends (Beath et al. 1937, Gissel-Nielsen 1971, Wells et al. 1980).

Aquatic plants at Kesterson had considerably higher selenium concentrations than terrestrial plants. Apparently, the majority of selenium was being retained in the aquatic system and was not readily moving into terrestrial soils. However, selenium concentrations in terrestrial plants and seeds at Kesterson were much higher than those found at Volta and occurred at concentrations greater than those known to be toxic to animals (Rosenfeld and Beath 1964, Arnold et al. 1973, El-Begearmi et al. 1977, Ort and Latshaw 1978). Seeds of several terrestrial plant species at Kesterson are consumed by aquatic birds (Appendix B, Connelly and Chesmore 1980, Euliss 1984, H.M. Ohlendorf unpubl. data); thus, there is a potential for accumulation of selenium in birds consuming parts of terrestrial plants in addition to the aquatic biota.

Boron

Subsurface drainwater transported to Kesterson also contained high concentrations of boron, and the biota had consistently higher concentrations than most samples from

Volta. Some were up to 52 times greater. Ohlendorf et al. (1986a) also found high boron concentrations at Kesterson in 1983. In this study, the highest boron concentrations ocurred in submergent aquatic plants (e.g. algae, diatoms, widgeongrass), and many of these are common waterfowl foods. Widgeongrass seeds contained very high boron concentrations with some samples reaching 3500 ppm. Boron concentrations in uncontaminated vegetation usually ranges from 1 to 100 ppm, with most samples having about 20 ppm or less (Bowen 1966, Boyd 1968, Boyd and Walley 1972, Cowgill 1974, Shacklette et al. 1978). Samples from both Kesterson and Volta contained higher boron concentrations than those reported as "normal" in the literature.

Concentrations of boron in plants and insects varied with species, pond, and season; this observation agrees with the data of Cowgill (1974) and Boyd and Walley (1972). They found that concentrations in cattails were highest in spring and generally decreased as the season progressed. Although cattails were not collected in spring at Kesterson, boron concentrations in leaves and rhizomes of cattails decreased from August to December. This decline in boron concentrations did not fit the normal pattern for most plants. Boron is not readily translocated from old to new growth, and it tends to concentrate in old leaves, with levels increasing as the growing season progresses (Hewitt 1963, Guha and Mitchell 1966, Boyd 1970a). Submergent aquatic plants and alkali bulrush from Kesterson generally followed this pattern and had the highest boron concentrations in December, while fathen and saltgrass followed similar patterns as cattails, with higher concentrations in August than in December. Few seasonal trends occurred in boron concentrations in aquatic insects.

The distribution of boron and selenium in plant parts was generally similar. Like selenium, boron concentrations were higher in rhizomes of emergent aquatic plants than in leaves and seeds. Leaves of emergent aquatic and terrestrial plants had higher concentrations than seeds, although terrestrial plants showed much variation in boron concentrations. In contrast to selenium, however, boron occurred at considerably higher concentrations in seeds than in leaves of widgeongrass.

Aquatic plants at Kesterson generally had higher boron concentrations than terrestrial plants. In contrast, Cowgill (1974) found that terrestrial plants had higher concentrations of boron than aquatic plants. Aquatic insects at Kesterson had boron concentrations similar to those in terrestrial plants and lower than those in most aquatic plants. Boron does not appear to bioaccumulate in the food chain, although levels in aquatic insects were still much higher at Kesterson than Volta.

Boron is an essential nutrient in plants (Eaton 1944, Boyd and Walley 1972, Beliles 1978), but its importance in animal diets has not been adequately demonstrated (Beliles 1978). High levels of boron in the environment have been shown to enhance vegetative growth for some plant species (Eaton 1944, Boyd and Walley 1972), but it can be toxic to others (Eaton 1944, Bingham and Garber 1970, Collier and Greenwood 1977). Substrate concentrations as low as 20 ppm (Bingham and Garber 1970) or 15 ppm (Maas 1986) have been reported to be toxic, and concentrations in some water and sediment samples at Kesterson were high enough to cause injury to some plants. Little is known about the effects of boron ingestion on bird reproduction, but Smith (pers. comm., U.S. Fish and Wildlife Service) found reduced reproductive success and increased embryo mortality in mallards fed a diet containing 1000 ppm boron. Boron concentrations of well over 1000 ppm (i.e. 3500 ppm) were found in widgeongrass seeds at Kesterson; thus, there is a potential toxic hazard to waterfowl consuming these plants. Considering the high boron concentrations in some plants and insects at Kesterson, further research is warranted to determine the impacts of high boron levels on the higher food chain.

Heavy Metals

Of the other eight metals measured, only molybdenum occurred consistently at higher (but not statistically significant) concentrations in the Kesterson biota than Volta. The other metals occurred at higher concentrations in biota and sediments from Volta, although most differences between sites were not large. Metals occurred at greater concentrations in sediments and biota than in water, and sediments usually had the highest levels. Concentrations observed in the biota at Kesterson and Volta were below those found in uncontaminated areas elsewhere (Boyd 1970b, Cowgill 1974, Gallagher and Kibby 1980, Taylor and Crowder 1983). Heavy metal concentrations in Kesterson biota are believed to be insufficient to be toxic to plants, insects, and higher food chain organisms.

Bioaccumulation

Bioaccumulation is simply the accumulation of chemical residues in an organism at levels greater than those in its food resource. Selenium has been reported to bioaccumulate in the food chain (Sandholm et al. 1973, Adams and Johnson 1977, Furr et al. 1979), while the pattern of boron accumulation is relatively unknown. Although bioaccumulation in the food chain was not observed for most metals, many (e.g. chromium, lead, molybdenum, nickel) have been reported to bioaccumulate in food chains (e.g. Cowgill 1973, 1974, Taylor and Crowder 1983, Giblin et al. 1980).

The majority of the biota accumulates selenium from their food source rather than directly from the water (Sandholm et al 1973, Fowler and Benayoun 1976), and selenium is available to most animals through plant uptake from soils (Rosenfeld and Beath 1964, National Research Council 1976, Nassos et al. 1980, Brown and Shrift 1982). Selenium concentrations at Kesterson increased from water to sediments to aquatic plants and from some of the plants to aquatic insects. Similar trends were observed at Kesterson (Saiki 1986a) and other selenium contaminanted sites (Cowgill 1973, 1974, Sandholm et al 1973, Adams and Johnson 1977, Furr et al. 1979, Holland 1980). Bioaccumulation rates/factors were similar for aquatic plants and insects (about 1000x), with plants concentrating selenium at slightly higher concentrations than insects. Both plants and insects bioaccumulated selenium to levels greater than those in their environment. Most aquatic insects at Kesterson contained lower selenium concentrations than rooted aquatic plants (e.g. widgeongrass, cattails), but higher concentrations than water, sediments, algae, and diatoms (Figure 5). Because the food of some aquatic insects includes algae, diatoms, and components of the water and sediments, but rarely rooted aquatic plants (Pennak 1978), these results are as one would expect. Mosquitofish (Saiki 1986b) at Kesterson also bioaccumulated selenium to levels greater than those in their foods (e.g. insects) (Figure 5). They bioaccumulated selenium up to 4000 times the minimum concentration found in water samples. In contrast, selenium concentrations in tissues of aquatic birds (Ohlendorf et al. 1986a) were not consistently greater than their food resources (e.g. aquatic plants and insects) (Figure 5).

Boron accumulated at lower rates than selenium in the ecosystem, but it followed similar patterns in some of the biota. As with selenium, aquatic plants accumulated the highest concentrations of boron, and results show bioaccumulation of boron in plants (Figure 7). Concentrations in plants and insects were greater than those in the abiotic environment, but insects bioaccumulated boron at lower levels than plants. Furthermore, boron concentrations in mosquitofish

(Ohlendorf et al. 1986a) were lower than those in aquatic plants and insects (Figure 7).

This study shows that aquatic ecosystems supplied with subsurface drainwater from seleniferous soils in California accumulated selenium and, in some biota, boron. Selenium concentrations were greater than those known to be toxic to animals or sensitive plants (Rosenfeld and Beath 1964, Ort and Latshaw 1978, Brown and Shrift 1982), but little is known about the accumulation rates in predatory birds and mammals that feed on birds and small mammals at Kesterson. However, one would expect these animals to accumulate selenium, in particular, at much higher levels. The concentrations of selenium and boron accumulated in the Kesterson ecosystem occurred in a relatively short period of time, and with longer exposure times the potential environmental hazards could greatly exceed the conditions observed in 1984.

Some insights can be drawn by comparing selenium to other contaminations (e.g. DDT, PCBs, mercury, lead) that have been extensively studied. DDT (Kieth and Hunt 1966, Butler 1969, Odum 1970, Bevenue 1976), PCBs (Prestt et al. 1970, Dustman et al. 1971, Sanders and Chandler 1976), and mercury (Hannerz 1968, Johnels and Westermark 1969, Peakall and Lovell 1972, Saha 1972) have been shown to bioaccumulate in the food chains. These contaminants bioaccumulate at higher rates than selenium did in this study. DDT bioaccumulates at the highest rates, with concentrations in fish and birds often over 100,000 times those in water (Mack et al. 1964, Odum 1970). PCBs (Jensen et al. 1969, Dustman et al. 1971, Sandlers and Chandler 1972) and mercury (Hannerz 1968, Johnels and Westermark 1969, Klein and Goldberg 1970) bioaccumulated in the food chain at similar rates as selenium with some marked exceptions. Sandlers and Chandler (1972) found bioaccumulation rates as high as 27,000 in marine ecosystems, and Hannerz (1968) found some water boatmen to contain mercury concentrations over 8000 times those in water samples. In contrast, boron accumulation at Kesterson followed a more similar pattern to lead contamination than the other pollutants. The lower trophic levels had the highest concentrations and bioaccumulation was not observed (Getz et al. 1977).

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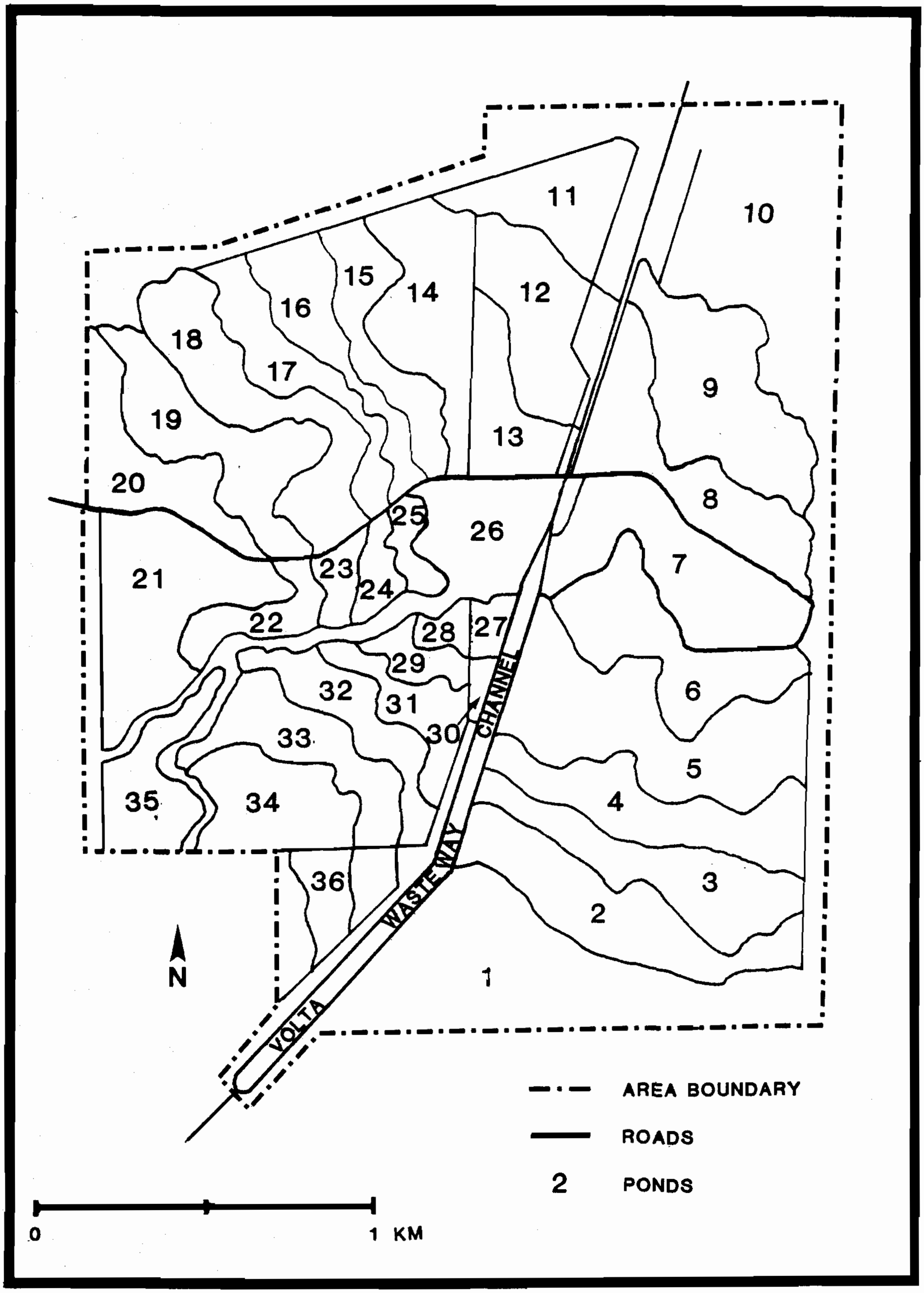
V. Appendices

Appendix A. Location of ponds at Volta Wildlife Management Area, California.



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Appendix A.

Appendix B. Percent occurrence of plants and invertebrates in esophagus of waterfowl collected at Kesterson Reservoir and Volta Wildlife Management Area during May to August of 1983 and 1984.

Item	Percent Occurrence					
	Mallard		Gadwall		C. Teal	
	Kesterson (N=8)	Volta (N=13)	Kesterson (N=6)	Volta (N=3)	Kesterson (N=5)	Volta (N=10)
Vegetation						
Atriplex spp.	-	8	-	-	-	-
Lemna spp.	-	8	-	-	-	-
Seeds						
Atriplex spp.	13	-	-	-	-	-
Calandrinia spp.	13	-	-	-	-	-
Cressa truxillensis	38	-	-	-	-	-
Eleocharis macrostachya	-	8	-	-	-	-
Heleochla schoenoides	25	46	-	-	-	10
Leguminosae spp.	13	8	-	-	40	20
Lolium spp.	-	-	17	-	-	-
Melilotus indica	-	15	-	-	-	20
Polypogon monspeliensis	-	8	-	-	-	-
Ruppia maritima	75	-	100	33	60	60
Scirpus robustus	-	31	-	-	-	10
Zannichellia palustris	13	23	-	33	60	10
Tubers						
Potamogeton spp.	13	8	-	33	-	-
Invertebrates						
Diptera						
Chironomidae Larvae	13	46	-	33	20	40
Ephydridae Larvae	-	31	-	33	-	20
Sciomyzidae Larvae	-	-	-	33	-	-
Stratiomyidae Larvae	-	-	17	-	40	-
Tabanidae Larvae	-	-	-	-	-	10
Coleoptera						
Curculionidae Adult	-	-	-	33	-	-
Dytiscidae Larvae	-	31	-	33	20	10
Dytiscidae Adult	-	-	-	-	20	10
Hydrophilidae Larvae	-	23	-	33	20	20
Hydrophilidae Adult	-	-	-	-	-	10
Ephemeroptera						
Baetidae Nymphs	-	38	-	-	-	-
Hemiptera						
Corixidae Adult	-	23	-	33	40	40
Notonectidae Adult	-	-	-	-	-	10
Saldidae Adult	-	-	-	33	20	-
Odonata						
Anisoptera						
Libellulidae Nymphs	13	-	-	-	-	-
Zygoptera						
Coenagrionidae Nymphs	38	8	17	-	20	-
Hydracarina						
Araneae	-	-	-	-	20	-
Cladocera						
Daphnidae	-	8	-	-	-	-
Mollusca						
Gastropoda	13	8	-	-	20	10

[a]Birds collected in 1983 were collected by H. Ohlendorf, U.S. Fish and Wildlife Service, Davis, California.

Appendix C. Single day waterfowl censuses conducted at Kesterson Reservoir and Volta Wildlife Management Area in May, August, and December of 1984.

	Number (Percent)					
	May		August		December	
Species	Kesterson[a]	Volta[b]	Kesterson[a]	Volta[c]	Kesterson[c]	Volta[c]
Mallard (*Anas platyrhynchos*)	43(38)	600(79)	174(85)	1196(11)	2(14)	5(2)
Gadwall (*Anas strepera*)	46(40)	60(8)	31(15)	375(3)	5(36)	-
Common Pintail (*Anas acuta*)	3(3)	22(3)	-	6306(56)	-	5(2)
Green-winged Teal (*Anas crecca*)	-	-	-	1975(18)	5(36)	-
Cinnamon Teal (*Anas cyanoptera*)	5(4)	80(10)	-	405(4)	-	-
American Wigeon (*Anas americana*)	-	-	-	15(<1)	-	-
Northern Shovelor (*Anas clypeata*)	-	2(<1)	-	955(8)	-	35(16)
Redhead (*Aythya americana*)	17(15)	-	-	-	-	-
Goldeneye (*Bucephala* spp.)	-	-	-	-	2(14)	-
Ruddy Duck (*Oxyura jamaicensis*)	-	-	-	-	-	175(80)
Total	114	764	205	11237	14	220

[a]CountsbyU.S.Fish and Wildlife Service,San LuisWildlife Refuge, Los Banos, California.
[b]Counts by authors.
[c]Counts provided by California Department of Fish and Game, Los Banos Wildlife Area, Los Banos, California.

Appendix D. Correlation of water chemistry parameters and relationship of plant and invertebrate biomass to water chemistry parameters, as demonstrated by simple correlations, stepwise multiple regression, and coefficents of determination.

	Significance by Multiple Regression (Simple Correlation Coefficient)				
Item[a]	Alkalinity	Conductivity	Se	B	R^2
Alkalinity		(-0.85)	(-0.73)	(-0.90)	
Water Depth	--[b]	--	--	--	
Ph	--	--	--	--	
Conductivity	(-0.85)		(0.80)	(0.83)	
Selenium	(-0.73)	(0.80)		(0.65)	
Boron	(-0.90)	(0.83)	(0.65)		
Distichlis spicata	NS[c] (-0.77)	NS --	NS --	S[d] (0.78)	0.62
Typha domingensis	NS --	NS --	NS --	NS --	
Ruppia maritima	NS --	NS --	NS --	NS --	
Zannichellia palustris	NS --	NS --	NS --	NS --	
R. maritima Seeds	NS --	S (0.72)	NS --	NS (0.67)	0.52
Z. palustris Seeds	NS --	NS --	NS --	NS --	
Corixidae	NS (0.65)	S (-0.78)	NS (-0.62)	NS (-0.77)	0.60
Chironomidae	NS (0.62)	NS --	NS --	NS --	
Stratiomyidae	NS (-0.65)	S --	NS --	S (0.85)	0.96
Ephydridae	S (-0.83)	NS (0.75)	NS (0.68)	NS (0.82)	0.68
Hydrophilidae	NS --	NS --	NS --	NS (0.64)	
Total Invertebrates	NS --	NS --	NS --	NS --	
Total Vegetation	NS (-0.73)	NS (0.76)	S (0.85)	NS --	0.72

[a]N=8
[b]--=Significant at P<0.05 by Pearson correlations.
[c]NS=Not significant at P>0.05 by stepwise multiple regression.
[d]S=Significant at P<0.05 by stepwise multiple regression.

Appendix E. Composition and abundance of plants in terrestrial habitat at Kesterson Reservoir, California.

INTRODUCTION

A variety of vegetation grows in terrestrial habitat at Kesterson Reservoir on islands within the ponds, water edges, pond dikes, and drained pond beds. Although the primary water supply for terrestrial vegetation is rainfall, these plants are indirectly affected by surrounding pond water and the elemental composition of that water. Furthermore, the banks and islands of some ponds at Kesterson were often flooded during winter. High salt, nutrient, boron, and selenium concentrations in Kesterson water (Chapter II and III) may affect terrestrial vegetation. This paper compares plant composition and abundance on islands at Kesterson to similar habitat at Volta Wildlife Management Area.

METHODS

Terrestrial vegetation was sampled on islands in pond 5 at Volta (Appendix A) and ponds 7 and 11 at Kesterson (Chapter II, Study Area). Samples were collected in 0.1 m^2 plots located along 60 m transects during May 1984. Transects were selected to represent characteristic vegetation of islands in each pond. Two transects were located in each pond with 10 plots per transect. Points were systematically located along each transect, 6 m apart with the first point located randomly. At each point, a random compass direction and a random distance of 1 to 3 m from the point determined where a plot would be placed. This procedure was repeated for every plot, producing 20 plots per pond.

Samples were collected by clipping vegetation at the ground surface. The harvested material was sorted by species, with seeds and vegetation combined. Dead plant material in a sample was separated from living tissues, because of difficulties in identifying species. Sorted plants were stored in paper bags and dried in a forced draft air oven at 65°C to a constant weight (72 hours). Dry weights were determined to the nearest 0.001 g, and biomass data were converted from g/0.1 m^2 to g/m^2.

Arithmetic means and 95 percent confidence intervals were calculated for all plant species. All analyses were conducted with transects from the same pond combined. A one-way analysis of variance was used to assess pond variability. Differences between pond means was analyzed by the Student-Newman-Keuls multiple range test (Snedecor and Cochran 1980).

RESULTS AND DISCUSSION

Few significant differences ($P<0.05$) between plant biomass means at Kesterson and Volta were found (Table 15). Mean dry weight of yellow sweet clover (*Melilotus indica*), spike rush (*Eleocharis macrostachya*), barley (*Hordeum geniculatum*), willowweed (*Polygonum lapathifolium*), and rabbit-foot polypogon (*Polypogon monspeliensis*) were significantly ($P<0.05$) greater at Volta than at Kesterson. Seeds of these genera provide a valuable food source for waterfowl (Krapu 1974, Serie and Swanson 1976, Connelly et al. 1980, Pederson and Pederson 1983, Euliss 1984), and these results indicate a greater food resource at Volta. Kesterson had a significantly ($P<0.05$) greater biomass of cressa (*Cressa truxillensis*) in pond 11 and rye grass (*Elymus triticoides*) in pond 7. Significant ($P<0.05$) differences occurred in total plant biomass in all ponds. Pond 7 at Kesterson had the greatest biomass (257.51 g/m^2), followed by Volta (217.40 g/ m^2), and pond 11 at Kesterson (145.04 g/m^2). Although Kesterson was found to have a significantly ($P<0.05$) greater aquatic plant biomass than Volta (Chapter II), it did not have an overall greater plant biomass in terrestrial habitat.

Both study areas are highly alkaline, while

Table 15. Mean biomass (g/m^2) and 95 percent confidence interval of plants found in sample plots on islands in ponds at Kesterson Reservoir and Volta Wildlife Management Area, 1984.

	Mean (+ 95% Confidence Interval)		
	Volta	Kesterson	
Plant	Pond 5	Pond 7	Pond 11
Atriplex patula	0.10 (0.01)	26.62 (23.25)	4.34 (3.74)
Bromus mollis	6.00 (10.67)	2.86 (2.81)	--
Bromus rubens	--	2.20 (3.19)	--
Carduus pycnocephalus	0.24 (0.52)	1.00 (1.53)	--
Centaurea melitensis	1.12 (1.64)	--	--
Cotula cornopifolia	--	--	0.11 (0.25)
Cressa truxillensis	--[a]	--[a]	4.30[b] (7.27)
Distichlis spicata	82.74 (30.25)	69.68 (39.19)	121.68 (45.14)
Eleocharis macrostachya	7.67[b] (6.22)	--[a]	--[a]
Elymus triticoides	--[a]	120.37[b] (108.22)	--[a]
Festuca megalura	--	0.13 (0.27)	--
Frankenia grandifolia	0.96 (1.57)	--	13.31 (24.46)
Geranium dissectum	--	tr	--
Grindelia camporum	0.93 (1.91)	--	--
Heleochla schoenoides	--	--	1.26

Table 15. Continued.

Hordeum geniculatum	9.74^{b} (8.29)	0.27^{a} (0.39)	$--^{a}$
Juncus textilis	18.75 (27.05)	--	--
Lythrum Hyssopifolia	--	tr	--
Malva parviflora	--	--	tr
Melilotus indica	82.96^{b} (48.87)	6.73^{a} (3.29)	0.03^{a} (0.03)
Polygonum lapathifolium	2.35^{b} (1.96)	$--^{a}$	$--^{a}$
Polypogon monspeliensis	10.38^{b} (6.16)	4.41^{a} (7.45)	$--^{a}$
Rumex crispus	0.38 (0.81)	--	--
Rumex pulcher	5.46 (2.69)	12.57 (7.99)	--
Spergularia media	--	0.34 (0.60)	--
Sporobolus airoides	--	20.23 (34.64)	--
Typha domingensis	0.18 (0.39)	--	--
Dead plant material	6.97^{a} (4.90)	87.34^{b} (54.94)	2.24^{a} (2.11)
Total Plants	217.40^{b} (45.21)	257.51^{c} (97.02)	145.04^{a} (47.86)

N=60

--Not observed

[a,b,c]Significance between means of an item is reported by the Student-Newman-Keuls Multiple Range test ($P<0.05$). Means not significantly different share the same letter and letters not in common indicate significance between those means. No letters behind means in a row indicate that the means are not significantly different.

Kesterson is also subjected to high salt and mineral concentrations in the ponds. The influence of Kesterson's water supply would be greatest on island edges and on islands that are periodically flooded. However, this influence is probably minimal and observed differences in species composition and abundance may be attributed to high variability in sample means, small sample size, differences in management techniques, and random distribution of plants.

Appendix F. Minimum detectable concentrations (ppm, wet weight) found in samples from Kesterson Reservoir and Volta Wildlife Management Area, 1984.

	Se	B	Cr	Mo	As	Cd	Cu	Pb	Hg	Ni
Water	0.0005	[a]	0.001	0.005		0.0005	0.005	0.0008	0.0002	0.004
Sediments	0.2	5.0		0.5		0.05			0.05	
Diatoms			0.1	0.1		--[b]	--	--	--	--
Filamentous Algae	0.05		0.1	0.1		--	--	--	--	--
Submerged Aquatic Plants	0.05		0.1	0.1		0.01				
Submerged Aquatic Seeds	0.05			--	--	--	--	--	--	--
Alkali Bulrush Rhizomes	0.05			--	--	--	--	--	--	--
Alkali Bulrush Seeds	0.05		0.1	0.1	0.05	--	--	--	--	--
Cattail Rhizomes	0.05			0.1	--	--	--	--	--	--
Cattail Leaves	0.05		0.1	--	--	--	--	--	--	--
Cattail Seeds	0.1		0.1	--	--	--	--	--	--	--
Saltgrass Leaves	0.1		0.1	--	0.05	--	--	--	--	--
Saltgrass Seeds	0.05		--	--	0.05	--	--	--	--	--
Fathen Leaves	0.05		0.1	0.1	0.05	--	--	--	--	--
Fathen Seeds				--	--	--	--	--	--	--
Australian Saltbush Leaves	0.05	--	--	--	--	--	--	--	--	--
Australian Saltbush Seeds	0.05	--	--	--	--	--	--	--	--	--
Yellow Sweet-Clover Leaves			--	--	0.05	--	--	--	--	--
Yellow Sweet-Clover Seeds	0.05		--	--	0.05	--	--	--	--	--
Brass-Button Seeds			--	--	0.05	--	--	--	--	--
Fiddle Dock Seeds	0.05		--	--	0.05	--	--	--	--	--
Alkali Weed Leaves			--	--	--	--	--	--	--	--
Alkali Weed Seeds			--	--	--	--	--	--	--	--
Water Boatmen		1.0		0.1	0.05					0.1
Damselfly Nymphs		1.0	0.1	0.1				0.03	0.02	0.1
Dragonfly Nymphs			--	--				0.05		
Beelte Adults			--	--		--	--	--	--	--
Fly Larvae		1.0	--	--		--	--	--	--	--

[a] Concentrations in all samples occurred above minimum detection limits.
[b] Samples not analyzed for this element.

Appendix G. Simple correlations of selenium and boron concentrations in water, sediments, widgeongrass, and water boatmen on water chemistry parameters from Kesterson Reservoir and Volta Wildlife Management Area, 1984.

	Water		Sediments		Widgeongrass		Water Boatmen	
	Se	B	Se	B	Se	B	Se	B
Conductivity	(0.57)[a]	(0.90)	(0.54)	NS[b]	(0.82)	NS	(0.81)	(0.56)
Alkalinity	(-0.79)	(-0.59)	(-0.52)	NS	(-0.61)	(-0.56)	NS	NS

[a]Significant at P<0.05 by Pearson Simple Correlations.
[b]Not significant.