DETAILED STUDY OF IRRIGATION DRAINAGE IN AND NEAR WILDLIFE MANAGEMENT AREAS, WEST-CENTRAL NEVADA, 1987-90

Part B. Effect on Biota in Stillwater and Fernley Wildlife Management Areas and Other Nearby Wetlands

Robert J. Hallock ***and*** **Linda L. Hallock, *Editors***
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CONVERSION FACTORS, VERTICAL DATUM, DEFINITION, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
acre	4,047	square meter
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per acre (acre-ft/acre)	0.3048	cubic meter per square meter
acre-foot per acre per year (acre-ft/acre/yr)	0.3048	cubic meter per square meter per year
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year
foot (ft)	0.3048	meter
foot per year (ft/yr)	0.3048	meter per year
gallon (gal)	3.785	liter
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
ounce (oz)	0.02957	liter
square foot per second (ft^2/s)	0.9072	square meter per second
square mile (mi^2)	2.59	square kilometer
ton per year (ton/yr)	0.9072	megagram per year
yard	0.9144	meter

Temperature: Degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) by using the formula °F = [1.8(°C)]+32.

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929, formerly called "Sea-Level Datum of 1929"), which is derived from a general adjustment of the first-order leveling networks of the United States and Canada.

Definition: The term "water year" refers to the 12-month period October 1 through September 30, during which a complete annual hydrologic cycle normally occurs. The water year is designated by the calendar year in which it ends. Thus, the year ending September 30, 1988, is called the "1988 water year."

Abbreviated water-quality units used in this report:

L (liter)
µg/g (microgram per gram)
mL (milliliter)
mg/L (milligram per liter)
ppt (part per thousand)
NTU (Nephelometric turbidity unit)
mg/kg (milligram per kilogram)
µm (micrometer)
µg/L (microgram per liter)
g (gram)
µS/cm (microsiemen per centimeter at 25°C)
g/L (gram per liter)
kg (kilogram)

DETAILED STUDY OF IRRIGATION DRAINAGE IN AND NEAR WILDLIFE MANAGEMENT AREAS, WEST-CENTRAL NEVADA, 1987-90

Part B. Effect on Biota in Stillwater and Fernley Wildlife Management Areas and Other Nearby Wetlands

Robert J. Hallock *and* Linda L. Hallock, *Editors*

Abstract

A water-quality reconnaissance investigation during 1986-87 found high concentrations of several potentially toxic elements in water, bottom sediment, and biota in and near Stillwater Wildlife Management Area (WMA). These results prompted the U.S. Department of the Interior to initiate a more detailed study in 1988 to determine the hydrogeochemical processes that control water quality in the Stillwater WMA and other nearby wetlands, and the resulting effects on biota, especially migratory birds.

The average historical size of the natural wetlands at Carson Lake and Stillwater Marsh, the water quantity, and the average dissolved-solids concentration and load in the water in these wetlands were estimated. Present wetland size is about 10 percent of historical size; the dissolved-solids load in these now-isolated wetlands has increased only moderately, but the concentration has increased more than seven-fold. Wetland vegetation has diminished and species composition has shifted to predominantly salt-tolerant species in many areas. Decreased vegetative cover for nesting is implicated in declining waterfowl production. Decreases in numbers or virtual absence of several wildlife species are attributed to degraded water quality.

Toxicity tests established that water in some drains and wetland areas was acutely toxic to some fish and invertebrates. Toxicity is attributed to the combined presence of arsenic, boron, lithium, and molybdenum. Rapid fluctuations in specific conductance and atypical ionic composition, which may increase acute toxicity, were observed in some drainwater. A strong relation was found between trace elements and both daily and average specific conductance.

Biological pathways are involved in the transport of mercury and selenium. Concentrations of selenium and mercury in drainwater were very low to below analytical reporting limits, but these elements had bioaccumulated in plants, and selenium had biomagnified in one trophic level (invertebrates) up to 10,000-fold. Selenium and mercury accumulated in plants, detritus, and invertebrates had been transported through irrigation drains to large wetland areas frequented by waterfowl and other wildlife, but no evidence of expected long-term selenium build-up since development was found in the wetlands. Several source areas of selenium and mercury were identified.

Hatch success of both artificially incubated and field-reared duck eggs was 90 percent or greater; no teratogenesis was observed. Boron and selenium concentrations in eggs were generally low—all below adverse effect levels. Mercury concentrations were also low except in eggs from Stillwater WMA, where about 30 percent of the eggs contained concentrations above the adverse effect level. Boron, mercury, and selenium concentrations in pre-flight juvenile ducks ranged from insignificant to levels associated with impaired survival. Boron concentrations were at or below effect levels in various duck species, but above effect level in coots (*Fulica americana*). Mercury concentrations in birds from Stillwater WMA, Carson Lake, and Carson Valley were above effect levels. Mean concentrations of selenium ranged from 30 to 77 micrograms per gram (µg/g) in birds from Fernley WMA and Massie and Mahala Sloughs, all above effect level. Survival of juvenile birds that had accumulated selenium, however, was not reduced. Field nest success was 26 percent and estimated overall production was about 2,400 ducklings from 6,800 breeding pairs. This poor production was attributed primarily to drought conditions and dissolved-solids accumulation that caused vegetative loss and exposed the nests to predators.

Maximum concentrations of mercury in muscle and liver tissue of waterfowl harvested from Carson Lake and Fernley WMA were 15.5 and 38.9 µg/g, wet weight, respectively, which exceeded the established human health criterion of 1.0 µg/g. Selenium concentrations in livers of juvenile waterfowl from Fernley WMA and Massie Slough were four times the established criterion for human health.

INTRODUCTION

In the last several years, concern has been increasing about the quality of irrigation drainage, and its potential adverse effects on human health, fish, and wildlife. Recent studies at several National Wildlife Refuges and Wildlife Management Areas (WMA) throughout the western United States have identified elevated concentrations of selenium and other trace elements that are a potential threat to biota within the management areas (Knapton and others, 1988; Lambing and others, 1988; Peterson and others, 1988; Radtke and others, 1988; Schroeder and others, 1988; Stephens and others, 1988; Wells and others, 1988; Hoffman and others, 1990; and Setmire and others, 1990). In 1988, the U.S. Department of the Interior (DOI) directed the U.S. Geological Survey, U.S. Fish and Wildlife Service, U.S. Bureau of Reclamation, and the U.S. Bureau of Indian Affairs to implement detailed studies that would provide information useful for mitigating the negative effects of irrigation-drainage water. The detailed studies were to provide information on (A) toxic constituents, (B) their effects on biota, and (C) a summary of significant findings.

The Stillwater WMA (and other nearby wetlands) in west-central Nevada (fig. 1) is one of several areas in the western United States selected for detailed examination of the mobilization, transport, and fate of potentially toxic constituents involving the biotic and abiotic environment.

Background

The changes that have occurred in the wetlands associated with the Newlands Irrigation Project in the Carson Desert are widely recognized and are partly summarized in a report by the U.S. Department of the Interior (1988). An overview of the increment of change that may be ascribed to irrigation drainage was needed to place the related DOI irrigation-drainage studies in perspective.

Prior to these investigations, few studies had documented the effects of the toxic components of irrigation drainage on biota in and near Stillwater WMA. The first comprehensive study of irrigation-induced water-quality problems was made during 1986-87 by Hoffman and others (1990). Henny and Herron (1989) studied irrigation-drainage-related contaminants in white-faced ibis (*Plegadis chihi*) at Carson Lake.

Several contaminants found in irrigation drainage are known to directly affect fish and invertebrates, and thus indirectly, birds; both fish and invertebrates are important in the diets of many migratory birds at Stillwater WMA. Aquatic invertebrates are a frequent food source for birds during reproduction because ingested invertebrates provide high energy food for rapid growth of young birds in preparation for migration. Salinity is often high at Stillwater WMA, and both water and biota contain elevated levels of

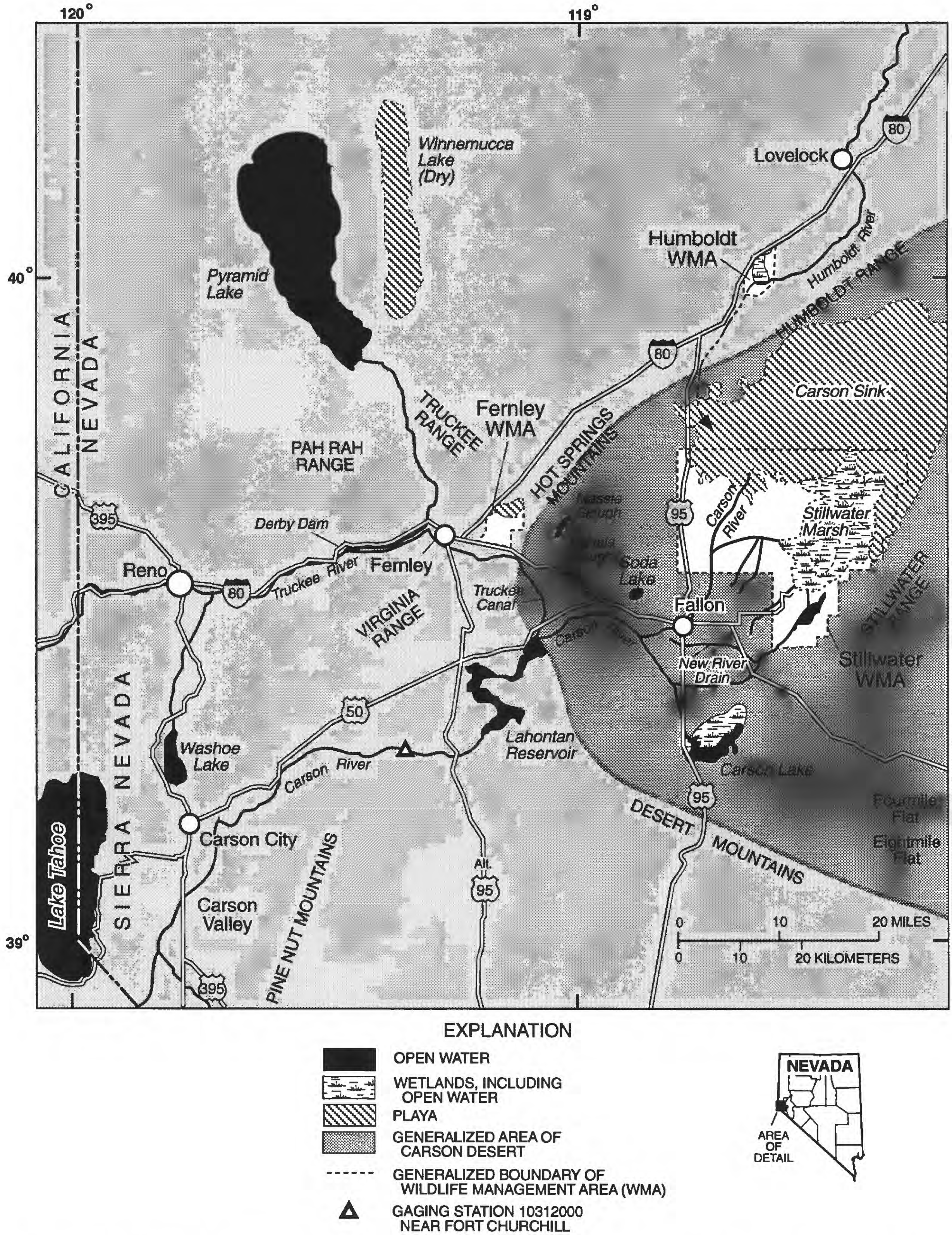

Figure 1. General physiographic features in the study area and western Nevada (Modified from Lico, 1992).

potentially toxic trace elements (Hoffman and others, 1990, p. 76-77). At Stillwater WMA, Largemouth bass (*Micropterus salmoides*), which once supported a popular sport fishery, are gone and the diverse fish forage base supporting American white pelicans (*Pelecanus erythrorhynchos*) is greatly reduced (U.S Fish and Wildlife Service, 1988, p. 132).

Some water-quality components associated with irrigation drainage may directly affect migratory birds. Both selenium and mercury have bioaccumulated and biomagnified in migratory bird tissues from the study area to the extent that reproduction may fail (Hoffman and others, 1990, p. 60, 67, 72, 77; Eisler, 1985, p. 38). High concentrations of selenium were found in juvenile migratory birds confined to wetlands that commonly contained less than the analytical reporting limit (<1.0 μg/L) of dissolved selenium concentrations in water. In these same wetlands, selenium concentrations in sediment (≤ 1.2 μg/g) were well below the level of concern (4.0 μg/g) recommended by Lemly and Smith (1987, p. 9). Selenium was found in shallow ground water affected by irrigated agriculture in and near the headwaters of TJ Drain (U.S. Bureau of Reclamation, 1987, p. B14). Most of the mercury in the study area originated from 19th century mining and milling practices in the middle Carson River basin (Smith, 1943, p. 247). The distribution of mercury throughout the study area is associated with floodways and channels of the Carson River that existed before construction of the Newlands Irrigation Project. Low concentrations of mercury were found in filtered sample water from the study area. The highest concentration of mercury in water, reported by Hoffman and others (1990, p. 36), was 1.1 μg/L in Lead Lake in Stillwater WMA.

Reproductive life phases are typically sensitive and vulnerable to the effects of contaminants. Trace-element toxicity is a possible contributing factor to the steady decline in waterfowl production in wetlands maintained by drainage from the Newlands Irrigation Project (U.S. Department of the Interior, 1988, p. E-7-E-10). In addition to the white-faced ibis found to be accumulating selenium and mercury in the breeding grounds at Carson Lake (Henny and Herron, 1989, p. 1032), deformed ibis chicks have been observed at Stillwater WMA (U.S. Fish and Wildlife Service, Fallon, Nev., unpublished data, 1987). Dead and dying waterfowl found in Carson Sink and in various parts of this study area (Stillwater WMA, Humboldt WMA, and Carson Lake) had selenium levels in liver tissue sufficiently high to cause toxicosis (> 30 μg/g), although necropsy reports did not identify selenium toxicosis as the immediate cause of death (Rowe and Hoffman, 1990, p. 39; Hoffman and others, 1990, p. 74). The primary effect of excessive dietary selenium on mallards (*Anas platyrhynchos*) is reproductive—reduced reproductive efforts, hatch rates, and duckling survival (Lemly and Smith, 1987, p. 5). Chronic sublethal mercury concentrations are also related to reduced reproductive success (Heinz, 1979, p. 398; Finley and Stendell, 1978, p. 54). Laboratory studies of boron as a dietary supplement showed reduced hatch rates, hatch weights, growth rates, and duckling survival (Smith and Anders, 1989, p. 943). Selenium, mercury, and boron were found in migratory birds, food-chain organisms, and sediment in the study area during the reconnaissance study by Hoffman and others (1990, p. 58, 62).

Wildlife from study-area wetlands have been used as food by humans for more than 4,000 years (Kelly, 1988, p. 11). Although the wetlands no longer support a popular fishery, harvest and consumption of waterfowl continues. When potential toxic elements, such as mercury and selenium, accumulate in waterfowl tissues, a concentration may be reached at which human consumption is inadvisable. During 1986-87, Hoffman and others (1990, p. 77) found indications that juvenile migratory birds, including waterfowl, in and near Stillwater WMA and Carson Lake were accumulating mercury and selenium in liver and muscle tissue. Some of the concentrations exceeded established criteria for human health. Cooper and others (1985, p. 56) identified a possible threat to human health from mercury in fish fillets taken from various wetlands in the Newlands Irrigation Project area, including Stillwater WMA.

Purpose and Scope

This report presents findings of the five detailed study elements that evaluate general and specific effects of irrigation drainage on biota and mechanisms or linkages related to these effects in wetlands in and near Stillwater WMA. The primary purpose in studying these wetlands was to assist remediation efforts in support of migratory waterfowl, a Federal trust responsibility; the common theme of these five elements is the possible adverse effects of irrigation drainage on migratory waterfowl. The five study elements, in order of presentation in this report, examine the historical conditions of the wetlands compared to the present, determine which potentially toxic trace elements are present in the area, explore pathways by which the trace elements move through the wetlands, determine the effects of the contaminants on waterfowl production, and consider human-health implications.

Because of the length and scope of this report, those primarily interested in the collective findings of all the studies may wish to pass the detailed sections and proceed directly to the summary section at the back of this report. The more technically oriented reader may wish to examine the individual sections for more detail.

This investigation was made and the report authored by U.S. Fish and Wildlife Service scientists. The report is published by the U.S. Geological Survey to maintain continuity with the other detailed-study reports for the area (Rowe and others, 1991; Lico, 1992; and Hoffman, in press). While the period of study was 1988-90, some biological data collected in 1987 were used to assess the concentrations of mercury and selenium in waterfowl.

Study Area

The Carson Desert hydrographic area (Rush, 1968, pl. 1) occupies a mostly flat area of about 2,020 mi^2 in the lower Carson River drainage basin. The area is about 70 mi east of Reno, and is one of the largest basin-fill valleys in northern Nevada. The Carson Desert includes natural wetlands at Carson Lake and—within the artificial boundaries of Stillwater WMA—Stillwater Marsh and the southern part of the Carson Sink (fig. 1). The Carson Sink is a nearly barren, flat, salt-encrusted playa occupying an area of about 400 mi^2 on the northern boundary of Stillwater WMA. In abnormally high precipitation years, wetlands may emerge in the Sink, supported by flow of the Carson River and, on occasion, overflow from the Humboldt River.

Historically, these wetlands were supported primarily by the Carson River, but since completion of the Newlands Irrigation Project, additional water has been imported from the Truckee River drainage basin to the Carson River by way of the Truckee Canal. The Carson River is a major tributary draining the eastern slopes of the central Sierra Nevada. As with most rivers associated with the Great Basin, its annual discharge patterns are highly variable.

Biological samples were collected from additional wildlife areas because of their proximity to Stillwater WMA, and because they are maintained by a combination of ground water and drainage from DOI irrigation projects. These other areas include the largely Project-created wetlands at Fernley WMA near Fernley, Nev., about 30 mi west of Stillwater WMA; Massie and Mahala Sloughs, about 25 mi west of Stillwater WMA; and the natural wetlands at Humboldt WMA (fig. 1).

Summary descriptions of climate, geology, soils, water use, hydrologic setting, wetland areas, and wildlife use were reported by Hoffman and others (1990) and Lico (1992).

Acknowledgments

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And, finally, we thank Ray J. Hoffman, Study Team Leader, and Carol A. Myers, Technical Editor, of the U.S. Geological Survey for their substantial efforts in making this a more concise and cohesive document.

(p. 7 follows)

ESTIMATED HISTORICAL CONDITIONS OF THE LOWER CARSON RIVER WETLANDS

To evaluate the effect of irrigation drainage on the wetlands of the lower Carson River, Carson Lake, Stillwater Marsh, and associated intermittent wetlands in the Carson Sink (fig. 1), an estimate was needed of the conditions prevailing before the onset of irrigation and development. These estimated historical wetland conditions were then compared to present and projected wetland conditions. To do this, it was necessary to distinguish between effects resulting from irrigation and those resulting from wetland management practices. Climatic changes, extreme variability of the streamflow of the Carson River, the cyclic nature of this variation, and the presence of lands irrigated with Carson River water upstream of the Newlands Irrigation Project are important considerations for the determination of historical conditions.

The historical flow, seasonal variation, average wetland size, and water quality were estimated on the basis of extrapolations from data in existing records, reports by early explorers, and archaeological findings. Early reports and evidence from archaeological sites were used to estimate the types and abundance of vegetation and wildlife historically present. Present conditions were determined from data collected for this study and from other recent State and Federal reports and data, particularly data analysis compiled in April 1988 by the U.S. Fish and Wildlife Service at Stillwater Wildlife Management Area for OCAP (Operating Criteria and Procedures) of the Newlands Project (U.S. Fish and Wildlife Service, 1988), which are summarized in Appendix E of the Final Record of Decision (U.S. Department of the Interior, 1988).

ESTIMATED HISTORICAL CARSON RIVER FLOW AND WETLAND SIZES

Commonly, the flow path of the unregulated Carson River was to Carson Lake, out through Stillwater Slough into Stillwater Marsh, then terminated in Carson Sink, as discussed by Morrison (1964, p. 104) and Russell (1885, p. 44-45) and shown in figure 2. That flow pattern will be followed in this discussion, with alternating consideration of inflow quantities, wetland sizes, and probable water losses along the downgradient flow path.

Unregulated Flow of the Carson River

Systematic records of streamflow and water quality of the Carson River and associated wetlands have been kept only during this century. Data extrapolated from the existing streamflow records were used to estimate a representative annual average[1] volume of water inflow to the wetlands before the initiation of irrigation (pre-1860) in the Carson Desert. This predevelopment inflow was then used to estimate an average wetland acreage that would have been maintained primarily by inflow of the Carson River. Because the annual streamflow of the Carson River is highly variable, the extrapolation included the following information, estimates, and assumptions:

[1]The term "average" is used here to indicate a representative situation—sometimes stable, sometimes subject to extreme fluctuation; it does not mean a mathematical average or a usual or "normal" situation.

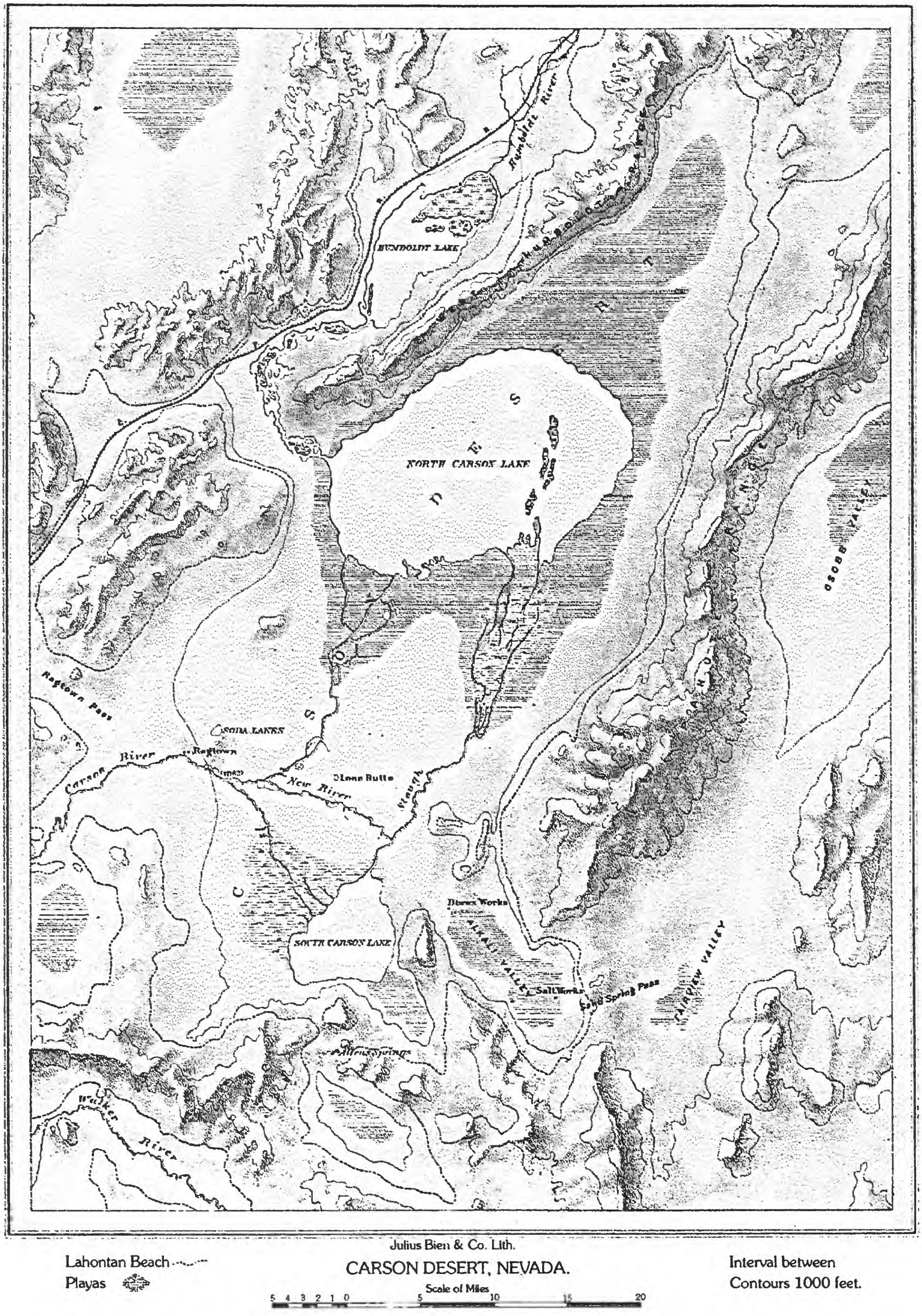

Figure 2. Reproduction of early map showing configuration of the lower Carson River basin before development (1880's). Note differences in name designations: in particular, "North Carson Lake," which is now part of Stillwater Marsh and Carson Sink, and "South Carson Lake," now designated simply Carson Lake. (Illustration was published in 1885 as Plate VII by I.C. Russell in U.S. Geological Survey Monograph 11, a report on ancient Lake Lahontan.)

(1) The average annual streamflow of the Carson River near Fort Churchill (U.S. Geological Survey station 10312000, approximately 50 river miles upstream from Carson Lake; fig. 1) was about 270,000 acre-ft (rounded) for the period of record, 1911-88 (Pupacko and others, 1989, p. 117).

(2) The average annual streamflow of the Carson River to Carson Lake and the connected Stillwater Marsh before agricultural development (pre-1860) was estimated to be equal to the present average annual streamflow near Fort Churchill **plus** the average annual flow of all water now consumed by agriculture upstream of that point. Other historical water losses, primarily seepage and evapotranspiration from the formerly more extensive wetlands associated with the upper river, were probably equal to other modern losses. These losses include seepage and evapotranspiration from reservoirs and canals, municipal uses, and agricultural uses in excess of the Alpine Decree[1] (Garry Stone, Federal Water Master, oral communication, 1990).

[1]The Alpine Decree is the adjudication of the Carson River water rights (California Department of Water Resources, 1991).

(3) About 56,000 acres are irrigated along the Carson River above Fort Churchill, with an annual evapotranspiration rate of 2.5 acre-ft/acre, as calculated from the Alpine Decree (California Department of Water Resources, 1991, p. 126), which results in an estimated 140,000 acre-ft of water being diverted from the Carson River and consumed annually. This amount is in agreement with the findings of Brown and others (1986, p. 30) that about 137,000 acre-ft of water may be consumed annually from the area above Lahontan Reservoir.

Thus, adding the estimate of agricultural consumptive use (about 140,000 acre-ft) to the Carson River discharge at Fort Churchill (about 270,000 acre-ft), the historical, unregulated annual average discharge of the Carson River at Fort Churchill was approximately 410,000 acre-ft. Based on the 1911-1988 period of record, the flow ranged from about 90,000 acre-ft/yr (sum of Carson River inflows above Fort Churchill [U.S. Geological Survey, 1978]) to about 940,000 acre-ft/yr (800,000, rounded [Frisbie and others, 1984, p. 127], plus 140,000). Seasonal variations in Carson River flows for the period of record (1919-1969) are discussed by Glancy and Katzer (1976, p. 34-42) and shown for the Fort Churchill station in figure 3 of this report.

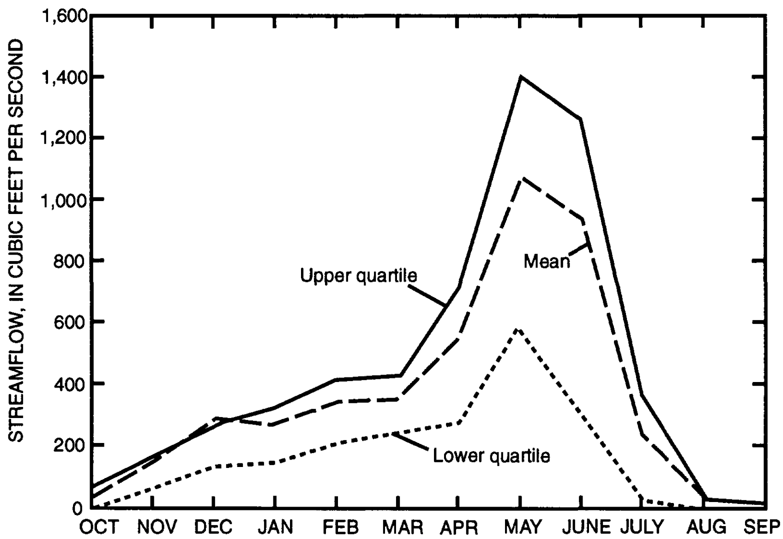

Figure 3. Mean monthly flow and quartile statistics, Carson River gage near Fort Churchill, USGS station 10312000, water years 1919-69. Modified from Glancy and Katzer (1976, p. 35).

Average Historical Size of Carson Lake

The areal extent of wetlands at Carson Lake when maintained by the entire average annual flow of the Carson River was dependant primarily on the annual evapotranspiration rates, wetland morphology, and magnitude of seasonal inflow. Natural variation in the course of the river where it entered the Carson Desert is discussed by Morrison (1964, p. 104). During recent geologic time, the Carson River usually flowed southeastward toward Carson Lake. As observed by Russell (1885, p. 44-45) in the mid 1800's, the Carson River also flowed northward to Carson Sink (North Carson Lake in fig. 2). The frequency of such flow-path changes over geologic time is unknown.

From his camp on Stillwater Slough in 1859, Simpson (1876, p. 85) observed a distinct line of cottonwood trees along the Carson River where it entered Carson Lake. E.M. Kern, a topographer with the Fremont Expedition of 1845, also reported seeing trees, probably cottonwoods, at the mouth of the Carson River from across the lake (Spence and Jackson, 1973, p. 51). These trees, large enough to be visible from a distance of at least 5 mi, as calculated from the map in figure 2, are an indication that a relatively stable geographic configuration of the lower Carson River had existed for 20-50 years prior to Kern's visit. For purposes of the present analysis, Carson Lake is assumed to have been a permanent wetland feature.

The maximum depth of Carson Lake at full pool is 10 ft, with the lake-bottom altitude at 3,909 ft above sea level (Hart and Bixby, 1922, p. 13) and the rim altitude at 3,919 ft (Morrison, 1964, p. 104). The maximum surface area of Carson Lake at the rim is about 34,000 acres. Russell (1885, p. 44-45; 1895, p. 108) observed the Carson Desert in the early 1880's, after the onset of early irrigation and after the Carson River had split with one part bypassing Carson Lake, thus reducing inflow to the lake. He described Carson Lake as varying in size and depth with the alternation of the seasons, generally outflowing through Stillwater Slough (1885, p. 68-69). The lake was discharging through the slough in June 1881, had an open water area of about 26,000 acres in 1882, and by September 1883, much of the lake appeared to be a swamp (Russell, 1885, p. 45, 69). Because emergent vegetation in this region is typically found where water depths are less than 3 ft, by September 1883 the surface of Carson Lake probably was at least 7 ft below its natural rim. This inferred difference in water level is greater than the evapotranspiration rate of 5 ft/yr (U.S. Department of the Interior, 1988, p. A-31). Outflow from Carson Lake in 1882 was nonexistent, as noted by Russell (1885, p. 45, 69). Apparently, the lake, at the time of his estimate of about 26,000 acres, was smaller than its maximum of 34,000 acres. About one fourth of the adjacent marsh, which was above the normal maximum lake-surface altitude, was probably intermittently flooded and may have covered about 4,000 additional acres (fig. 2). For purposes of this discussion, then, the maximum wetland acreage of Carson Lake and the adjacent marsh land is estimated to have been about 38,000 acres.

Large variations in the Carson River streamflow, both seasonal and annual, would have affected the size of Carson Lake seasonally. Typically, the seasonal flow patterns vary from low flow from August through November, to a slow increase through March, and finally to a spring peak late in April that falls off by July (fig. 3). Seasonally diminishing streamflows of the Carson River usually limit agriculture in the basin above Fort Churchill by July 15 (Garry Stone, Federal Water Master, oral commun., 1990).

The summer and fall streamflow in the Carson River may regularly have been insufficient to maintain Carson Lake, and the lake size may have peaked at the rim in early summer, then decreased. The estimated 4,000 acres of adjacent marsh is assumed, for purposes of this discussion, not to change in size. The seasonal variation noted by Russell (1885, p. 68-69) may have been usual. Richard Burton, in 1860 (1963, p. 551), found the water to be about a mile away from a Pony Express station (at the southwestern edge of the lake), but the following summer DeQuille (1963, p. 28) observed that the water was again up to the dock of the station. A summer-fall evaporative loss of 3 ft in depth would have reduced the surface of Carson Lake from a possible maximum of about 34,000 acres to about 29,000 acres. The lake size also has been periodically reduced by drought (Morrison, 1964, p. 104; Russell, 1895, p. 108). Thus, on the basis of the discussion above, the historical average wetted surface area of both open water and adjacent marsh at Carson Lake was less than the historical maximum, 38,000 acres, and is conservatively estimated to be 27,000 acres (table 1). This lesser acreage amount is used in the subsequent water-consumption estimate for Carson Lake.

Table 1. Estimated historical (predevelopment) wetland acreage compared to projected wetland acreage at Carson Lake and the combined wetlands of Stillwater Marsh and Carson Sink

{All values have been rounded]

Wetland area	Wetland Acreage: Predevelopment estimate (1845-60): Range	Wetland Acreage: Predevelopment estimate (1845-60): Average	Wetland Acreage: Projected average[1]
Carson Lake (South Carson Lake in figure 2)	[2]25,000-[3]38,000	27,000	5,000
Stillwater Marsh and Carson Sink (North Carson Lake and adjacent marsh lands in figure 2)	[2]0-200,000	120,000	[4]11,000
TOTAL (rounded)		150,000	16,000

[1] U.S. Fish and Wildlife Service, 1988, p. 19, fig. 21.
[2] Estimated minimum size associated with the 1911-88 period of Carson River flow records.
[3] Includes about 4,000 acres of adjacent marsh land.
[4] Includes 3,000 acres of historical Stillwater Marsh located within the Canvasback Gun Club (C. Clifford Creger, U.S. Fish and Wildlife Service, written commun., 1992).

Flow Through Stillwater Slough

In 1861, DeQuille described Stillwater Slough as 60 ft wide, with vertical banks 8-10 ft high, having no grass along the stream, and cutting through the barren sandy plain with only scattered clumps of sage and greasewood, which is typical of an intermittent waterway in this area (DeQuille, 1963, p. 36-37). The absence of hydrophytic vegetation in this channel also supports the contention that summer-fall flow in the Carson River was regularly insufficient to maintain flow through Stillwater Slough. Evapotranspiration losses at Carson Lake reduced the flow of the Carson River before it discharged through Stillwater Slough to Stillwater Marsh. These losses also decreased the duration of flow in the Carson River system below Carson Lake. With 27,000 acres average surface area and an evapotranspiration rate of 5 ft/yr, Carson Lake would have consumed about 140,000 acre-ft of water per year. Subtracting this from the unregulated average annual flow in the Carson River, about 410,000 acre-ft, leaves an annual average flow of 270,000 acre-ft to pass through Stillwater Slough into the wetlands—Stillwater Marsh plus Carson Sink.

Average Historical Size of Stillwater Marsh

The wetted area of Stillwater Marsh and the downgradient playa wetlands (much of Carson Sink) were more variable in size than Carson Lake because of the cumulative evapotranspiration losses in these shallow, sequentially distributed wetlands (Morrison, 1964, p. 104). Because there are no early quantitative estimates of the size of Stillwater Marsh—a series of interconnecting wetlands and ponds flowing generally from south to north, the average size of the Marsh must be estimated using other approaches. Archaeological evidence and pollen cores indicate that a relatively permanent marsh existed in the Stillwater area for the last 4,000 years (Kelly, 1988; Warburton and others, 1990, p. 74), an area known to have been regularly inhabited by man, and by other water-dependent species.

Stillwater Marsh was called Stillwater Lakes by Morrison (1964, p. 104). That observation implies enough water depth (at least 3 ft) to possibly preclude the growth of emergent vegetation and maintain open water areas. Minor variations in topographic elevations (5-15 ft) may be responsible for the formation of these "lakes" at Stillwater Marsh (Raven and Elston, 1989, p. 33). These depressions, by their proximity to flow from Stillwater Slough and by retaining water, gave a degree of permanence to these wetlands compared to the relatively flat areas of Carson Sink.

Raven and Elston (1989, p. 64, 69) have defined two broad categories of historical wetlands at Stillwater, namely "marsh" and "playa," based on soil types and hydrologic characteristics. Both wetland types supported human occupation and water-dependant biota. "Marshes" were those areas which characteristically had enough differences in topography to maintain a combination of open water, emergent vegetation, and upland sites suitable for human habitation. In the absence of detailed land surveys prior to development of Lahontan Valley, the historical amount of each wetland type is uncertain. Elevations determined from U.S. Geological Survey 7.5-minute quadrangle maps indicate that up to 55,000 acres of wetlands were possible in what is now (1993) the Stillwater National Wildlife Refuge. Therefore, wetland acreage could have ranged from 0 to 55,000 acres. Classification of wetland types on current U.S. Geological Survey 7.5-minute quadrangle maps indicates that wetlands at full pool consisted of an average of approximately 15,000 acres of marsh and 40,000 acres of playa (C. Clifford Creger, U.S. Fish and Wildlife Service, Fallon, Nev., written commun., 1992). These areas are consistent with a predictive model based largely on soil types, hydrology, and topography developed by Raven and Elston (1990, p. 123-34).

Carson River inflow through Stillwater Slough was seasonally intermittent. Parts of Stillwater Marsh were subjected to seasonal drying, as were the margins of Carson Lake. Although a graded change in evaporation losses would be predicted as the marsh diminished, it is conservatively estimated that 75 percent of this wetland, about 11,000 acres, would remain wetted and lose water at a rate of 5 acre-ft/yr. This lesser acreage is used **only** in the subsequent water consumption estimate for Stillwater Marsh.

Stillwater Marsh would have been dry only once during the period of record for the Carson River (1911-1988), resulting from the drought of water-years 1976-77.

Estimated Flow into Carson Sink Wetlands

Average water loss by evapotranspiration from the estimated 15,000 (full-pool) acres of Stillwater Marsh would have been 56,000 acre-ft, assuming that 25 percent of the area was seasonally dry. Thus, the 270,000 acre-ft of Carson River water entering the marsh by way of Stillwater Slough each year would be further reduced to an average of about 210,000 acre-ft before entering wetlands in the Carson Sink.

Estimated Size of Carson Sink Wetlands

Wetland acreage in the Carson Sink maintained by Carson River water was, as it is now, generally ephemeral. Ephemeral wetlands are typically shallow, receiving only a few inches of water at the distal edges, and tend to evaporate completely—or nearly so—before the next inflow season. Under unregulated conditions, average Carson River flow would have refilled Carson Lake and Stillwater Marsh and begun to flow into the Carson Sink during winter. Most flow would have reached the sink following spring snow melt or occasional rain-on-snow events. During the spring, wetlands in the southeastern portion of the Carson Sink may have been characterized by having large volumes of flowing water relatively low in dissolved solids. This portion of Carson Sink wetlands may have been wetted for as long as 6 months in most years. In response to decreasing Carson River inflow and increasing evapotranspiration rates in the summer, the palustrine regime would have ceased and the wetlands would have rapidly receded in size and depth to zero or some variable minimum size. Wetlands at the advancing edge of water during peak flow events would have been the most ephemeral, persisting only a few weeks.

Approximately 40,000 acres of playa wetlands on the Carson Sink within the confines of the present (1993) Stillwater National Wildlife Refuge also contain human occupation sites and evidence of water-dependent biota (C. Clifford Creger, U.S. Fish and Wildlife Service, Fallon, Nev., written commun., 1992).

Two accounts of water on the Carson Sink provide a basis from which to estimate an average wetland depth. This, combined with the average Carson River inflow, is used to estimate the average size of wetlands in the Carson Sink.

During September 1929, Sperry (1929, p. 1-3) surveyed the wetlands on the Carson Sink at the mouth of the Carson River. At that time, the river emptied into the Sink in the vicinity of what is now Fallon NWR, adjacent to Stillwater and topographically similar—mostly flat with shallow sloughs and low rises. Sperry considered the water supply to be deficient that year and below normal, and reported the water to be mostly less than 1 ft deep, with a few ponds 2.5-3 ft deep. In addition to alkali bulrush (*Scirpus maritimus*) beds, he saw blackened basal stalks that "coat long reaches of the higher ground and indicate an enormous extension of big beds during wet seasons." His observation of "carpets" of sago pondweed (*Potamogeton pectinatus*), some in mature fruit, left exposed by the receding waters, indicates that the water receded rapidly and suggests fairly rapid decreases in wetland size in the fall.

During the 1980's, the Carson Sink was inundated by flood flows from both the Carson and Humboldt Rivers. This is considered an anomalous event; flooding on that scale last occurred in the 1860's. The 1980's occurrence created unusual physical and water-quality conditions, and is of interest here primarily because of observations of water depth made at various times during the inundation.

Between July 1984 and February 1985, flood water inundating Carson Sink and Stillwater Marsh covered about 212,000 acres of surface area to a maximum depth of nearly 12 ft (Rowe and Hoffman, 1990, p. 37). At that size, the average depth would have been 8 ft and the volume about 1,700,000 acre-ft. In mid-January of 1987, water in the Carson Sink had receded to less than 180,000 surface acres, with an average depth of 2 ft and a maximum of 6 ft (Rowe and Hoffman, 1990, p. 37). The volume of water in the Carson Sink would then have been less than 360,000 acre-ft.

Although it is recognized that wetlands on the Carson Sink were dynamic, an average depth is needed to estimate the extent of wetlands which may typically have been maintained by the Carson River. Based on the observations by Sperry (1929) and Rowe and Hoffman (1990), 2 ft is a reasonable estimate for an average depth. Using this 2-ft depth, the 210,000 acre-ft inflow from the Carson River could have seasonally flooded an average of 105,000 surface acres of wetlands on Carson Sink. This area represents an average of maximum wetland sizes that could be anticipated from the flows of the 1911-1988 period of record for the Carson River.

The Carson Sink wetlands may have varied in size from 0 to 190,000 surface acres, based on fluctuations of the Carson River alone during the 78-year period of record. The low point, zero, would have occurred with flow similar to that of water-year 1977 (the second year of the 1976-77 drought) when the Carson River flow would not have reached the Carson Sink. The maximum, 190,000 acres, is based on the flow of the Carson River during water-year 1983. The adjusted flow of the Carson River at Fort Churchill in water-year 1983 was about 940,000 acre-ft (800,000 acre-ft, rounded [Frisbie and others, 1984, p. 127], plus 140,000 acre-ft from assumption no. 3 in the subsection "Estimated Historical Carson River Flow and Wetland Sizes"), and the inflow to the sink from the Carson River through Stillwater Marsh is estimated to have been about 750,000 acre-ft. Based upon a linear relationship of surface areas and water volumes observed by Rowe and Hoffman (1990), this 750,000 acre-ft would have inundated about 190,000 surface acres on the Carson Sink, with an average depth of nearly 4 ft and a maximum of 8 ft. Some of this water would be expected to remain on the sink into the following year. Under these extreme hydrologic conditions, parts of Stillwater Marsh also would be flooded.

ESTIMATED HISTORICAL WATER QUALITY

Little information about the historical water quality of the lower Carson River system exists, but explorers and local residents of the mid to late 1800's reported good water (presumably potable, in the historical sense), plentiful vegetation, and abundant wildlife at various locations in the lower Carson River basin and its wetlands.

In June 1859, Simpson (1876, p. 85) visited Carson Lake and wrote the following:

We are encamped at the head of the outlet from Carson Lake into the sink of Carson, where our only fuel is dry rush. This outlet is about 50 feet wide and 3 or 4 feet deep, and voids the lake rapidly into its sink, which is some 10 or 15 miles to the northeast of us. The water is of a rather whitish, milky cast, and though not very lively, is yet quite good. The Carson River to the northwest, where it empties into the lake, can be seen quite distinctly, marked out by its line of green cottonwoods.

The name of the river and lake was given by Colonel Fremont, in compliment to Kit Carson, one of his celebrated guides.

The alluvial bottom about Carson Lake is quite extensive and rich, as the luxuriant growth of rushes shows, and could, I think, be easily irrigated. The only drawback to its being unexceptionable for cultivation in every part is its being somewhat alkaline in places, particularly toward its southern portion. Curlew, pelican, and ducks, and other aquatic birds frequent the locality, and the lake is filled with fish.

Wuzzie George, a Native American residing in Lahontan Valley in the early 1900's and a keen observer of natural things, referred to the abundance of submergent vegetation in the Stillwater marshes (U.S. Fish and Wildlife Service, 1952, p. 19), an indication of water clarity. Hart and Bixby (1922, p. 15) found Carson Lake in 1922 to be slightly alkaline, with very little accumulation of salts on the edges, and with "vegetation [that] ... indicates the absence of an excess of harmful salts." At Stillwater Marsh, the remains of freshwater clams (*Anadonta sp.*), fish, mink (*Mustela sp.*), and river otter (*Lutra sp.*) in archaeological sites indicate the marsh had higher water quality than at present. The wetland ecosystem in the southern inflow area of Stillwater Marsh would have flourished with natural flushing, but water in the ephemeral wetlands on the Carson Sink would have accumulated salts. The fluctuating north and west margins of this ephemeral marsh probably resembled the barren areas associated with current managed wetlands, where water with dissolved solids concentrated beyond the tolerance level of aquatic plants is disposed of through evaporation.

Historical water-quality conditions were estimated using period-of-record data on streamflow and dissolved solids for the Carson River at the Fort Churchill gage. The average measured dissolved-solids concentration at the Fort Churchill gage for the period 1970-88, the only data available, was 218 mg/L and ranged from 70 to 454 mg/L (Ray J. Hoffman, U.S. Geological Survey, written commun., 1990). Although the average Carson River streamflow measured at Fort Churchill has decreased because of upstream diversions, the recent average dissolved-solids load at Fort Churchill (about 90,000 ton/yr) is assumed, for the purpose of the present analysis, to be about equal to the average historical dissolved-solids load. Although predevelopment loads did not include post-development contributions of dissolved solids from irrigation returns and sewage disposal, this assumption should result in a reasonable estimate of an upper limit for predevelopment dissolved-solids loads and concentrations. The average historical (1845-1860) concentration of dissolved solids entering Carson Lake is estimated to be about 170 mg/L. This concentration was determined by computing the ratio of the average volume of water for the period 1970-88 to the historical volume of water, then multiplying by the average dissolved-solids concentration for the period of record and adding an estimate for natural accretion (see footnotes 7 and 8 in table 2):

(300,000 acre-ft / 410,000 acre-ft) 218 mg/L
+ 10 mg/L = 170 mg/L (rounded).[1]

Historically, an estimated annual average of about 410,000 acre-ft of water reached Carson Lake by way of the Carson River; most of it overflowed to Stillwater Marsh. The water entering Carson Lake, with an estimated dissolved-solids concentration of 170 mg/L, carried a probable dissolved-solids load of about 95,000 ton/yr to the wetlands (table 2). This estimated load to the wetlands provides a benchmark for understanding baseline water-quality conditions that existed in Carson Lake, Stillwater Marsh, and the Carson Sink.

[1]The estimated historical dissolved-solids concentrations presented in this section are intended solely as a historical baseline for comparison with existing water quality of wetlands in the lower Carson River basin receiving irrigation drainage. Because of variation of flow and the high evaporation rate, the average conditions described herein may have been greatly exceeded at times; thus, the estimated predevelopment concentrations should not be used to set downstream water-quality standards.

Table 2. Estimated historical (predevelopment) and recent or projected water quantity and dissolved-solids concentrations and loads for Carson River, Carson Lake, and Stillwater Marsh. (Estimated historical dissolved-solids concentrations should not be used to set water-quality standards for wetlands in the study area)

[Abbreviations: acre-ft, acre-feet; ft/yr, foot per year; mg/L, milligrams per liter; ton/yr, tons per year]

	Carson River at Fort Churchill gaging station	Carson Lake	Stillwater Marsh
Water quantity (acre-ft)			
Historical (1845-60)	[1]410,000	[2]410,000	[3]270,000
Recent (1970-88) or projected by OCAP[4]	[5]300,000	[6]25,000	[6]55,000
Dissolved-solids concentration (mg/L)			
Historical (1845-60)	[7]160	[7,8]170	[7,8]270
Recent (1970-88) or projected by OCAP[4]	[7]220	[9]1,170	[9]1,170
Dissolved-solids load (ton/yr)[10]			
Historical (1845-60)	89,000	95,000	99,000
Recent (1970-88) or projected by OCAP[4]	90,000	40,000	88,000

[1] Estimated historical unregulated discharge at Fort Churchill gage (average annual streamflow for period of record plus upstream consumptive use; see text for details).

[2] All of Carson River flow estimated to enter Carson Lake.

[3] Water entering Stillwater Marsh estimated by using total inflow to Carson Lake (410,000 acre-ft), minus evaporation rate (5 ft/yr) multiplied by average wetland acreage of Carson Lake (27,000, rounded; table 1).

[4] OCAP (Operating criteria and procedures for Newlands Project) projection for 1992 and beyond (U.S. Fish and Wildlife Service, 1988).

[5] Recent (1970-88) annual average (R.J. Hoffman, U.S. Geological Survey, written commun., 1990).

[6] Estimated acreage projected for OCAP (table 1) multiplied by evaporation rate (5 ft/yr).

[7] Calculated from quantity and loads: $C = \frac{L}{Qf}$

where

C is concentration, in mg/L;

L is load, in ton/yr;

Q is quantity (streamflow), in acre-ft; and

f is factor for converting mg/L to tons (0.00136).

[8] Estimate includes calculated natural accretion of dissolved solids along the stream channel (R.J. Hoffman, U.S. Geological Survey, written commun., 1990).

[9] U.S. Fish and Wildlife Service, 1988, p. 51.

[10] All values calculated from estimated discharge and concentration $(L = C \times Q \times f)$.

The average wetted surface area of Carson Lake (27,000 acres) would have lost, through evapotranspiration, about 140,000 acre-ft of water annually. This loss of water from Carson Lake would have increased the dissolved-solids concentration in the remaining 270,000 acre-ft of water to about 260 mg/L as it discharged through Stillwater Slough. Because of its shallow depth and shape, Carson Lake would have exchanged water easily with the inflow. The average flow of the Carson River was about 2.5 times greater than the lake's maximum volume, thus long-term concentration of dissolved solids in Carson Lake would not have occurred, and the dissolved-solids load leaving the lake would have been similar to the inflow, about 95,000 ton/yr. Because the average volume of the outflow from Carson Lake is about 10 times the volume of Stillwater Marsh, essentially the same dissolved-solids load would have passed through the Marsh into Carson Sink. The dissolved-solids concentrations, however, would have been higher and more variable in these lower wetlands than in Carson Lake.

Several early reports are available that describe water quality in Stillwater Slough and Carson Lake. Kern (Fremont Expedition of 1845) said of the water at the outlet of Carson Lake that it was "indifferently good" (Spence and Jackson, 1973, p. 52). Stillwater Slough water was described as "quite good" by Simpson (1876, p. 85). DeQuille, in the summer of 1861, described the water at the south end of Carson Lake as having the taste of decayed tules, but found the water in the upper slough to have a "touch of alkali" and at the lower end—at the mouth of the sink, "a strong alkali twang"; he sent an Indian several hundred yards into the marsh for drinking water (1963, p. 28, 38, 42). After 60 years of agricultural activities (1862-1922), the dissolved-solids concentration of the water in Carson Lake was still only about 1,000 mg/L (Hart and Bixby, 1922, p. 15). For comparison, the maximum permissible dissolved-solids concentration in Nevada public water supplies is 1,000 mg/L. Dissolved-solids concentrations would have fluctuated seasonally when the lake surface regularly dropped below its natural rim in the fall and during droughts. As an example, Professor F.W. Clarke found a dissolved-solids concentration of about 1,500 mg/L in a water sample collected from Carson Lake in October 1863, a year after the Carson River was diverted from the lake during the floods of 1862 (Russell, 1885, p. 44, 69).

Approximately half the streamflow of the Carson River would have come during peak snowmelt runoff from April through mid-July, then in most years would have diminished abruptly. This pattern would have resulted in dissolved-solids concentrations that were more variable in Stillwater Marsh than in Carson Lake. In most instances, dissolved-solids concentrations in Carson Lake and much of Stillwater Marsh would not have been a limiting factor to the biota known to have existed in the system. From examination of pollen in a core of Lead Lake sediment, scientists of the Desert Research Institute found that the wetland water had been alternately brackish and fresh (Warburton and others, 1990, p. 73-74). Because of the irregular topography of Stillwater Marsh, some wetland areas may have been poorly flushed and occasionally bypassed by the flow of the Carson River.

Although Carson Lake and Stillwater Marsh currently are hydrologically isolated, the dissolved-solids loads projected under OCAP were summed (128,000 ton/yr) and compared to historical load (99,000 ton/yr) to assess the extent of change. While the projected load is estimated to increase somewhat—about 30 percent—over the historical load, the projected concentration would increase greatly—about 400 percent. Such a large increase in concentration is significant because living organisms respond physiologically to concentration rather than to load. Although the historical dissolved-solids concentration in Carson Lake would have increased as a result of evapotranspiration, the concentration in the water as it was flushed into Stillwater Marsh may have averaged 270 mg/L (see footnotes 7 and 8 in table 2) because of the higher river flows at that time. This concentration would have been representative of conditions throughout most of Stillwater Marsh following the spring flow peak.

The extrapolated estimates and existing reports indicate that the predevelopment water supply was probably adequate and of suitable quality to support healthy wetlands and their associated plants, fish, and wildlife. In the absence of agricultural irrigation, which has been shown to mobilize salts and trace elements such as arsenic, boron, selenium, molybdenum, and lithium (Hoffman and others, 1990, p. 31-38), and a corresponding increase in dissolved-solids concentrations, the water reaching Carson Lake and Stillwater Marsh in predevelopment time (pre-1860) was of better quality than water reaching the wetlands today.

Historical water quality in the ephemeral wetlands of Carson Sink, however, would have varied greatly. Under a representative average condition, 210,000 acre-ft of fresh water (about 270 mg/L, dissolved solids) would have passed into these ephemeral wetlands, flushing the area near Stillwater Marsh. Regular flushing in the spring would have created conditions favorable for aquatic vegetation and many forms of wildlife. Sperry (1929, p. 1-2) reported a wide variety of both submergent and emergent vegetation and wildlife in the sink, including extensive beds of alkali bulrush and sago pondweed. Alkali bulrush tolerates brackish water ranging from a specific conductance of 995 µS/cm (about 650 mg/L, dissolved solids) to 25,800 µS/cm (about 16,800 mg/L, dissolved solids). Sago pondweed grows in water containing as much as 16,800 mg/L, dissolved solids (25,800 µS/cm; Stewart and Kantrud, 1972, p. D5, D21, and D25). Archaeological sites that were occupied by humans are found in the playa habitat within the Carson Sink. These sites are similar to those in Stillwater Marsh, indicating the presence of wetland plants and animals (C. Clifford Creger, U.S. Fish and Wildlife Service, Fallon, Nev., written commun., 1992). Thus, these sites probably had potable water, in the historical sense, during periods of human use.

Water-quality characteristics are different when the Carson Sink is filled. Such an event, anomalous under current managed conditions, occurred between 1982 and 1988 when large quantities of relatively dilute flood water from both the Carson and Humboldt Rivers filled Carson Sink to a depth of nearly 12 ft (average 8 ft). In July 1983, specific conductance of flood water in the Carson Sink near Humboldt Slough was 4,700 µS/cm (about 3,100 mg/L, dissolved solids), but by January 1987 water in the Carson Sink had reached a dissolved-solids concentration of 20,000 mg/L (Rowe and Hoffman, 1990, p. 37). This concentration cannot be accounted for by evaporative water loss alone; much of the dissolved solids probably resulted from redissolving salts previously deposited in the sink. During this event, no vascular aquatic plants grew in the sink. Fish flourished during the first years, then perished when the dissolved-solids concentrations of water became intolerably high as the water evaporated. A similar cycle probably occurred in the 1860's; the water in Carson Sink was 20 ft deep in 1863, according to Morrison (1964, p. 104).

In summary, the historical condition of the Carson River-Carson Sink system was a flush-through pattern with most of the runoff occurring in the spring. Runoff flowed into Carson Lake, overflowed into Stillwater Marsh, and then created extensive ephemeral wetlands in the Carson Sink. Almost the entire 410,000 acre-ft (average annual flow) of Carson River with a probable low average (<300 mg/L) concentration of dissolved solids, entered the wetlands. The wetlands would have been largest in the spring, decreasing by evapotranspiration through the summer and fall. Salts deposited primarily in the sink by evaporating water would have been redissolved by the flushing action of subsequent spring peak flows and carried farther out into the sink. The distal edges of the wetlands would normally have been brackish, and the farthest reaches, at times, even more saline.

VEGETATION

Early reports of the study area describe a biologically productive marsh with a great diversity of vegetation. In 1845, when Kern reported timber at the mouth of the Carson River, he also described Carson Lake as bordered by "a thick growth" of bulrush about 30-40 yards wide at the mouth of the river (Spence and Jackson, 1973, p. 51-52). Simpson (1876, p. 85-86) called the alluvial bottom around the lake in 1859 "extensive and rich, as the luxuriant growth of rushes shows." Bailey (1898, p. 3) described Stillwater Marsh as "... half shallow lake, half tule swamp [which] extends for 20 miles along the valley bottom and furnishes enough salt grass, sedges, and tules to winter many thousand head of stock and a breeding ground for great numbers of water and shore birds."

Early in this century, Sperry (1929, p. 1-3) described the vegetation in the southwestern part of Carson Sink. At that time, alkali bulrush dominated the marsh, and cattail *(Typha sp.)* was common. Spike rush *(Eleocharis acicularis)* was abundant. Open water areas contained abundant stands of sago pondweed, horned pondweed *(Zannichellia palustris)*, and algae. The old high-water line was marked by iodine brush *(Allenrofea sp.)*, below that was a bank of pickle weed *(Salicornia sp.)*, and all around, even out in the mudflats, were patches of salt grass *(Distichlis spicata)*.

Wuzzie George described Stillwater Marsh of the early 1900's as abundant in both submergent and emergent vegetation; alkali bulrush was the most common emergent, followed by hardstem bulrush (*Scirpus acutus*) and cattails (U.S. Fish and Wildlife Service, 1952, p. 19).

At Stillwater Marsh, inflow water was sufficient to maintain luxurient wetland vegetation until 1967 when regular winter water releases from Lahontan Reservoir for power generation were discontinued. During the early 1950's, cattails were the dominant emergent species in the marsh, followed by alkali bulrush, then hardstem bulrush, at a ratio of 4.5:1.5:1 (U.S. Fish and Wildlife Service, Fallon, Nev., 1952, written commun.). A quantitative survey in Stillwater Marsh in 1959 found a diversity of vegetation. Emergent vegetation was then dominated by alkali and hardstem bulrushes and submergent plants by horned pondweed, sago pondweed, and western pondweed (*Potamogeton filiformis*). Other submergent plants observed by the U.S. Fish and Wildlife Service included coontail (*Ceratophyllum demersum*), muskgrass (*Chara sp.*), widgeon grass (*Ruppia maritima*), and curly-leaf pondweed (*Potamogeton crispus*). Some submergent plants, such as horned and sago pondweeds and widgeon grass, are relatively insensitive to high concentrations of dissolved solids (Stewart and Kantrud, 1972, p. D25; Steward and others, 1963, p. 50). The abundance of these submergent plants, as well as more sensitive species in Stillwater Marsh in 1959, indicates the presence of a mixture of fresh and brackish water at that time (U.S. Fish and Wildlife Service, 1969).

In the Stillwater WMA, coontail and other less salt-tolerant pondweeds that were abundant in the 1959 survey have decreased, not only in total abundance but also relative to the more tolerant species, such as widgeon grass and sago pondweed. The abundance of some plants, such as western pondweed, is correlated with freshwater inflow. Cattails are extremely sensitive to increased dissolved-solids concentrations, whereas alkali and hardstem bulrushes tolerate higher concentrations (Stewart and Kantrud, 1972, p. D21); cattails in Stillwater WMA are now found only in scattered patches.

Information from U.S. Geological Survey topographic maps (Carson Lake and Fallon quadrangles) published in 1951 indicates that vegetation has also diminished at Carson Lake by about 50 percent in the last 30 years. Today, much of Carson Lake is a pasture for livestock. Much of the remaining water area is entirely devoid of vascular aquatic vegetation, and emergent vegetation is reduced to relatively small stands of bulrush near the inflow from drains.

WILDLIFE

Historically, the wetlands of the Carson Lake-Stillwater area supported a large and diverse assemblage of animals as well as plants. Archaeological studies have determined that the wetland areas were used extensively by native people for a period exceeding 4,000 years (U.S. Department of the Interior, 1988, p. F1; Kelly, 1988, p. 11), an indication that the early (pre-1860) wetlands were a more productive and reliable habitat than those existing today. Little information is available to quantify the abundance of wildlife in the study area prior to irrigation diversion, but reports from early explorers and archeologists indicate that populations and diversity of wildlife were much greater than exist today.

According to Simpson (1876, p. 85), the marsh supported abundant fish populations. Simpson wrote, "... the lake is filled with fish...[the Indians] have piles of fish lying about drying, principally chubs and mullet." DeQuille (1963, p. 33) saw Indians with "several fine strings of fish" in 1861 and the Indians fishing nearby were having "first-rate luck"; one had caught four nice fish in a few minutes. Fish bones are commonly found in archaeological sites, suggesting that fish were a significant food source for the people; skeletal remains of tui chub (*Gila bicolor*) and tahoe sucker (*Catostomus tahoensis*) are abundant at archaeological sites in Stillwater Marsh (Greenspan, 1988, p. 315-326). Both fish species are tolerant of wide ranges of dissolved solids. Lahontan cutthroat trout (*Onchorhynchus clarki henshawi*), although not widely distributed, were found in some Stillwater archaeological sites (Smith, 1985, p. 177). Lahontan cutthroat trout are tolerant of dissolved solids up to approximately 12,000 mg/L (Taylor, 1972, p. 7), but are sensitive to high water temperature. Historical water quality in Carson Lake and the southern part of Stillwater Marsh should not have been a limiting factor in the survival and distribution of cutthroat trout at most times, but changing habitat and water temperature resulting from water-level fluctuations may have been.

River otter and mink, both fish-eating animals, were present and used by the native people (Schmitt, 1988, p. 272). Pelicans (*Pelecanus erythrorhynchos*), also fish eaters, were "characteristic" of the area (Simpson, 1876, p. 86).

Freshwater clams and aquatic snails (gastropods) were once abundant throughout the wetlands. Simpson (1876, p. 86) observed in 1859 that the shores of Carson Lake were covered with clam shells, and Russell (1885, p. 69) reported various species of freshwater clams and snails in Carson Lake. Drews (1988, p. 329-333) found evidence that clams were a food item at various sites in Stillwater Marsh. Sperry (1929, p. 3), surveying the adjoining wetland in Carson Sink in 1929 (now Fallon NWR), found that clams, frogs (*Rana sp.*), and snails (*Physa sp.)* were common, and that muskrats (*Ondatra sp.*) were reported as abundant throughout Carson Sink.

Mink and otters are absent from the wetlands today, as are frogs and turtles. Muskrats are no longer abundant. Fish populations are greatly reduced, and the species composition has changed since historical times. Most of the native fishes are now absent from most areas; Lahontan cutthroat trout are entirely absent. Several species of non-native fishes, primarily sport fish, were introduced early in the century, but most have decreased to remnant numbers. Introduced Largemouth bass (*Micropterus salmoides)* was a major fishery until the 1970's, when the population virtually disappeared. Today, only remnant populations of freshwater clams remain in Stillwater Point Reservoir and in the D-line Canal, the areas with the lowest dissolved-solids concentration.

Historical references record the abundance of pelicans, curlews (*Numenius americanus*), other shore birds, ducks, geese, and other aquatic birds (Simpson, 1876, p. 85-86; Bailey, 1898, p. 3; DeQuille, 1963, p. 28-32). Shore birds, including curlew, are largely insectivorous and tend to frequent shallow, sparsely vegetated ephemeral water areas and mud flats—wetland types that historically covered thousands of acres on the Carson Sink in the spring and are now scarce. None of the birds are entirely absent today, but none could be termed abundant and some, such as the curlew, are uncommon.

PRESENT/PROJECTED WETLAND CONDITIONS

Court-ordered Operating Criteria and Procedures (OCAP) for the Newlands Project, to be fully in effect in 1992, were evaluated in detail by the U.S. Department of the Interior (1988). An estimate of projected wetland conditions was made, based on data for inflow of water from all sources available for wetland maintenance between 1967 and 1986 and on surveys of varying reliability, made in September for many years, of all major wetlands in the area. The managed wetlands at Carson Lake and Stillwater Marsh (Stillwater WMA and Canvasback Gun Club) under the 1992 institutional (OCAP) constraints, are used here to represent present/projected wetland conditions. It is important to note that the Carson River no longer flows through Carson Lake and thence to Stillwater Marsh. Both wetlands are isolated; are maintained with drainwater, operational releases, and occasional flood flows; and are manipulated with man-made water-control structures.

Recent (1967-1986) average wetland sizes for Carson Lake and Stillwater Marsh were 10,000 and 14,000 acres, respectively. Under OCAP, flow to these primary wetlands, and their average size, are reduced about 50 percent (U.S. Department of the Interior, 1988, p. E5; U.S. Fish and Wildlife Service, 1988, fig. 5, p. 52). Under projected managed conditions, an average 25,000 acre-ft of water would maintain about 5,000 wetland acres at Carson Lake, and an average 55,000 acre-ft of water in Stillwater WMA Marsh (including the Canvasback Gun Club) would maintain about 11,000 acres of wetlands. This projected total of average wetland sizes in Carson Lake and Stillwater Marsh (16,000 acres) is about 11 percent of the estimated historical sum of 150,000 average wetland acres in and near Carson Lake, Stillwater Marsh and Carson Sink. Present wetland conditions are not directly comparable to historical conditions because most of the water now available is used for maintenance of permanent wetlands. In contrast to the natural pattern of the unregulated, historical Carson River (fig. 3), with an abrupt spring runoff peak, the water to Stillwater WMA, dictated by agricultural practice, comes in a reduced, protracted flow from March through November, without a substantial flushing flow in the spring (U.S. Fish and Wildlife Service, 1988, fig. 8). In addition, much of the remaining flow is managed by artificial structures to create permanent wetlands consuming about 5 acre-ft/acre of water per year. Because of this management, present wetlands are smaller but more permanent than historical wetlands supported by a given amount of water. To allow comparison, under OCAP the average 16,000 acres projected to remain in Carson Lake and Stillwater Marsh would require at least 80,000 acre-ft/yr of water. However, the dissolved-solids concentrations in the inflow water of Stillwater Marsh and Carson Lake are now, respectively, about four to seven times greater than historical concentrations; wetland flushing is restricted only to years with exceptionally high streamflow.

Water quality projected for the wetlands was described by the U.S. Fish and Wildlife Service (1988, p. 50). Dissolved-solids concentrations in water entering primary wetlands would average 1,170 mg/L, as projected for OCAP. The dissolved-solids concentration of the Carson Lake inflow is about seven times the estimated historical concentration of 170 mg/L of solids for the Carson River, and the Stillwater Marsh inflow is about four times more concentrated than the estimated 270 mg/L historical Stillwater inflow by way of Stillwater Slough. Again, the reader is cautioned that the historical estimates are just that—estimates—and should not be used beyond that intended for this report.

In Stillwater WMA, dissolved solids are progressively concentrated through evapotranspiration as inflow water is stored for waterfowl use then moved through sequentially arranged ponds (table 3). These are historical ponds with water-control structures added. Under past management practices, the initial wetland would concentrate inflowing dissolved solids by nearly four times, to about 4,600 mg/L, and the next sequential wetland would further concentrate dissolved solids by six times, to about 28,000 mg/L (U.S. Fish and Wildlife Service, 1988, table 7).

Present concentrations of dissolved solids would rarely have occurred in the historical flow-through wetlands at Carson Lake and Stillwater Marsh, but they may have routinely occurred in parts of the more ephemeral wetlands in the Carson Sink. For example, high dissolved-solids concentrations were measured in the Carson sink during the 1980's (Rowe and Hoffman, 1990, p. 37). Present water-quality conditions in parts of Carson Lake and Stillwater Marsh are limiting to some aquatic plants and animals. In addition, trace elements toxic to fish and invertebrates are being released from Carson Desert soils by agricultural drainage and are entering these wetlands, as discussed in the next section on toxicity.

In summary, the pattern of water flow, quality of the water, and the size and quality of the resultant wetlands, as well as vegetation and wildlife, have all changed dramatically since the onset of irrigation in the late 1800's.

Table 3. Concentration factors between wetland units and recent and projected concentrations of dissolved solids, Stillwater Wildlife Management Area

[Values are based on data collected by the U.S. Fish and Wildlife Service (1988)]

Wetland unit[1]	Recent average dissolved solids (mg/L) (1967-1986)	Approximate concentration factor	Projected average dissolved solids (mg/L)
Wetland inlet flow	600	[2]2	1,170
Primary unit	2,360	4	4,610
Secondary unit	14,180	6	27,600
Tertiary unit	28,400	2	55,200

[1] Primary, secondary, and tertiary units refer to a series of shallow ponds that receive water progressively more concentrated with dissolved solids.

[2] Initial change in dissolved-solids concentrations resulting from irrigation practices.

TOXICITY OF IRRIGATION DRAINAGE AND ITS EFFECT ON AQUATIC ORGANISMS

The wetlands in Stillwater Wildlife Management Area (WMA) are managed primarily to support migratory waterfowl. Many water-dependent migratory birds require a variety of fish and invertebrates in their diets. As a result of irrigation drainage, water in Stillwater WMA has an unnaturally high salinity, and both water and biota contain elevated concentrations of potentially toxic trace elements that can affect fish and invertebrates (Hoffman and others, 1990, p. 76-77). For example, Stillwater WMA can no longer sustain a Largemouth bass (*Micropterus salmoides*) population (U.S. Fish and Wildlife Service, 1988, p. 132), and invertebrate density is low. Toxicity tests were conducted to assess the suitability of water from various drains and wetland areas to support fish and invertebrates.

METHODS

Sample Collection

Water samples were collected at sites in Stillwater WMA on Paiute Diversion Drain, D-Line Canal, Hunter Drain, Lead Lake, Stillwater Point Diversion Drain, Stillwater Point Reservoir, and TJ Drain (including one USGS well near TJ Drain). Sampling sites are shown in figure 4.

Composite water samples were collected daily from each drain location during August 9-18, 1988. Each sample consisted of water collected at 15-minute intervals during a 24-hour period by an ISCO model 2710 automatic composite sampler. Water was pumped from the drain through Teflon tubing into 19-L, acid-washed, glass collection containers. The containers were held in ice baths during the collection period to keep the samples at approximately 4°C during the day. Water samples from Lead Lake and Stillwater Point Reservoir were collected daily as "instantaneous" samples and, as such, represent the quality of the water at the time of sampling. Onsite toxicity tests were made with portions of these samples collected daily from each location. Principal constituents and properties of each water sample (temperature, pH, dissolved oxygen, hardness, alkalinity, turbidity, specific conductance, salinity, and calcium, sulfate, and chloride) were measured on-site daily. Ammonia and nitrate were measured near the beginning, middle, and end of the toxicity tests.

A portion of the composite water collected daily was used for determination of additional inorganic constituents (magnesium, sodium, potassium, silica, phosphorus, arsenic, barium, boron, lithium, mercury, molybdenum, selenium, strontium, vanadium, and zinc). These subsamples were collected in 1-L, linear polyethylene bottles that had been previously washed with soap and water, rinsed with tap water, soaked in concentrated nitric acid, and rinsed twice with deionized water. Samples were filtered through a 0.4-µm polycarbonate filter and preserved with 2 mL of ultrapure nitric acid for in the laboratory analysis. Chemical analyses of the water were made by Environmental Trace Substances Research Center (Columbia, Mo.). Spiked samples, blanks, and replicates prepared onsite were included as quality-assurance samples (Peden, 1986).

A one-time collection of water from an observation well near TJ Drain was made by U.S. Geological Survey personnel using a bailer and according to standard methods (Claasen, 1982). The well water, which represented potential seepage to the drain, was tested for acute toxicity and analyzed for trace-element concentrations.

A one-time collection of water from all drains also was made for analysis of potentially toxic man-made organic constituents. Analysis was made by the U.S. Geological Survey National Water Quality Laboratory, Denver, Colo. The data are on file at the U.S. Geological Survey, Nevada District Office, Carson City.

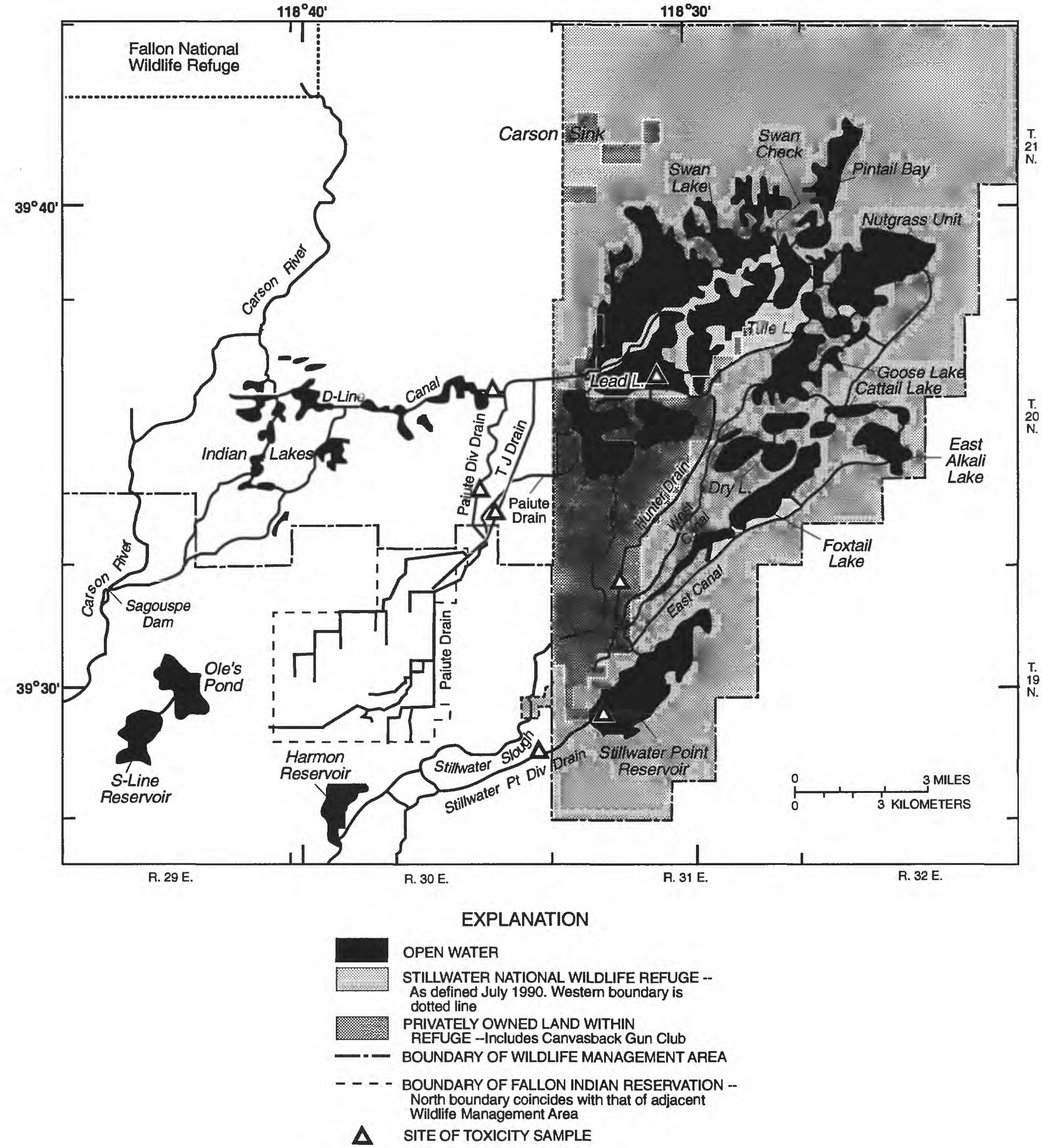

Figure 4. Locations of toxicity sampling sites and important hydrologic features in and near Stillwater Wildlife Management Area. (Map modified from Lico, 1992.)

Toxicity Assessments

Toxicity tests were made using a portion of the daily composite water sample from each location to renew the test solution daily throughout the test period. The species tested were bluegills (*Lepomis macrochirus*), larval fathead minnows (*Pimephales promelas*), and daphnids (*Daphnia magna*). Daphnids and fathead minnow larvae were obtained from cultures at the National Fisheries Contaminant Research Center (NFCRC), Columbia, Mo., and were maintained onsite in well water (hardness, 283 mg/L as $CaCO_3$; alkalinity, 255 mg/L as $CaCO_3$; pH, 7.8) that had been transported from NFCRC. Bluegills (≤0.1 g) were obtained from the Missouri Department of Conservation, shipped to Stillwater WMA, and transferred into the NFCRC well water for 48 hours of observation prior to use. Using Hunter Drain water, in which salinity exceeded 15 ppt, additional tests were made with salt-tolerant species—sheephead minnow (*Cyprinodon variegatus*) larvae, and mysid shrimp (*Mysidopsis bahia*). These organisms were obtained from the U.S. Environmental Protection Agency (USEPA) Laboratory in Gulf Breeze, Fla.

Tests were made as static renewals under appropriate 10-day test procedures (USEPA, 1985; American Society for Testing Materials, 1988). All organisms were fed freshly hatched brine shrimp (*Artemia*) twice daily. Tests with daphnids and fathead minnow larvae included 2 replicates per treatment and 10 organisms per replicate. Tests with bluegills consisted of 2 replicates per treatment and 5 organisms per replicate. Treatments included full-strength water and dilutions of 50, 25, and 12.5 percent. Dilution water for each test was reconstituted to the appropriate hardness, alkalinity, specific conductance, and pH for that test-location water by the addition of major cations and anions using Instant Ocean and deionized water. By reconstituting dilution water to the same ionic composition as the drainwater, consistent concentrations of constituents such as calcium, magnesium, sodium, potassium, chloride, and sulfate were maintained for all treatments for each sampling site. All sampling sites were evaluated using this reconstituted water as a diluent and as a control. In addition, Paiute, TJ, and Stillwater Point Diversion Drains were also assessed by using water into which they discharged (Paiute and TJ into D-Line, and Stillwater Point Diversion Drain into Stillwater Point Reservoir) as diluent and control. The NFCRC well water provided a second control to evaluate the condition of test organisms throughout the tests. Dissolved-oxygen concentrations exceeded 40 percent saturation in all tests. Acceptability of a test required that control mortality not exceed 10 percent.

Evaluation of potential toxicity problems in the Stillwater area included a total of 35 concurrent tests on water samples:

Sample site	Dilution source	Number of tests
Paiute Diversion Drain	Reconstituted water	3
Paiute Diversion Drain	D-Line Canal water	3
TJ Drain	Reconstituted water	3
TJ Drain	D-Line Canal water	3
Stillwater Point Diversion Drain	Reconstituted water	3
Stillwater Point Diversion Drain	Stillwater Point Reservoir water	3
Stillwater Point Reservoir	Reconstituted water	3
Lead Lake	Reconstituted water	3
Hunter Drain	Reconstituted water	5
D-Line Canal	Reconstituted water	3
TJ Drain ground water	Undiluted water	3

During the tests, mortality was recorded daily for each species. Bluegills were weighed and measured to assess growth at the initiation and termination of the test. A subsample of daphnids was preserved on the first day of the test and the surviving adults were also preserved on the final day of the test for later examination. For daphnids, time to first brood production, total number of broods, and number of young per brood were recorded as measures of reproductive success. Temperature, pH, and dissolved oxygen were measured daily in each beaker prior to renewal of test solutions.

Chemical Analyses

Principal constituents and properties, along with ammonia and nitrate, were determined using standard methods (magnesium, sodium, potassium, silica, phosphorus, arsenic, barium, boron, lithium, mercury, molybdenum, selenium, strontium, vanadium, and zinc).

Filtered water samples to be analyzed for inorganic constituents were digested in 100-mL borosilicate glass beakers that had been cleansed by a concentrated nitric acid, 30-minute, reflux cycle. About 40 mL of the digested sample was combined with 15 mL of concentrated nitric acid and 2.5 mL of concentrated perchloric acid, then evaporated over low heat until only 1 mL remained. This digestate was diluted to 50 mL with ultrapure water and analyzed for selenium and arsenic by hydride generation atomic absorption. The remaining digestate was analyzed for additional elements with an inductively coupled plasma spectrophotometer. Mercury was determined by cold vapor atomic absorption. Analytical procedures are described in detail by the U.S. Fish and Wildlife Service (1985).

All results were within 20 percent of confidence intervals for certified or recommended concentrations for the reference materials. Of the samples analyzed, 10 percent were blanks and 20 percent were blind replicates and spiked samples. No values for blanks exceeded analytical reporting limits for any element (table 4).

Daily water-quality measurements for the seven surface-water sites are presented in the supplemental data tables at the back of this report. A summary of ranges is shown in table 6.

Water samples for analysis of manmade organic constituents were extracted three times in the laboratory at both acidic and basic pH with methylene chloride. The extracts were concentrated to about 1 mL, combined with an internal standard, and analyzed by gas-chromatography, electron-impact, mass spectrometry. Surrogate compounds were added to each sample prior to extraction to verify method recoveries (Wershaw and others, 1987). The analytical results are discussed in the subsection titled "Stillwater Point Diversion Drain and Stillwater Point Reservoir."

Table 4. Analytical reporting limits for selected inorganic constituents in water (from Environmental Trace Substances Research Center, Columbia, Mo.)

[All units in micrograms per liter, except where indicated; mg/L milligrams per liter]

Element	Concentration	Element	Concentration
Calcium (mg/L)	0.002	Copper	2
Magnesium (mg/L)	.002	Iron	5
Sodium (mg/L)	.02	Lead	40
Potassium (mg/L)	1	Lithium	.5
Sulfate (mg/L)	1	Manganese	5
Silica (mg/L)	.01	Mercury	.3
Chloride (mg/L)	.15	Molybdenum	20
Phosphorus (mg/L)	.10	Nickel	100
Aluminum	30	Selenium	.3
Antimony	40	Silver	20
Arsenic	.5	Strontium	4
Barium	1	Thallium	3
Beryllium	1	Tin	10
Bismuth	60	Titanium	4
Boron	20	Tungsten	2
Cadmium	2	Vanadium	2
Chromium	10	Zinc	2
Cobalt	10		

RESULTS OF TOXICITY TESTS

Paiute Diversion Drain and D-Line Canal

Water from Paiute Diversion Drain diluted with D-Line Canal water was not acutely toxic to bluegills, fathead minnow larvae, or daphnids (table 5). No substantial mortality occurred in tests with water from Paiute Diversion Drain regardless of dilution water, and no mortality was recorded for any species exposed to water from D-Line Canal. No sublethal responses were identified in daphnids exposed to water from either location. Daphnids produced equal numbers of young in all treatments, with one brood produced in every treatment on day 8. For all treatments, mean number of young per brood ranged from 8.1 to 9.4. Microscopic examination of adults at the end of the test revealed production of eggs for a second brood and substantiated the continued reproductive development that would be expected in healthy organisms. Concentrations of constituents in Paiute Diversion Drain and D-Line Canal water were similar, and daily fluctuations in water quality were minimal during the study period (table 6). Neither mercury nor selenium was detected in any water sample. In addition, aluminum, antimony, beryllium, bismuth, chromium, cobalt, copper, iron, nickel, silver, tin, titanium, thallium, and tungsten did not exceed reporting limits.

TJ Drain

Water from TJ Drain was acutely toxic to bluegills, fathead minnow larvae, and daphnids (tables 7 and 8). Cumulative mortality in 100-percent TJ Drain water was similar for fathead minnows and bluegills, and ranged from 85- to 90-percent mortality after 9 days of exposure. No mortality was observed in well-water controls, reconstituted-water controls, or 100 percent D-Line Canal water also used as control. Daphnids were more sensitive than were fish species to the two highest drain-water concentrations. Total mortality of daphnids occurred in full-strength drainwater after 6 days and in the 50-percent dilution by the end of the test; no substantial mortality occurred in the 12.5-percent dilution. No daphnid reproduction occurred in the TJ Drain water regardless of dilution water. Control daphnids in reconstituted water reproduced on day 8, with a mean brood size of 9.6; a first brood (9.3 young) was also produced on day 8 in the D-Line Canal control water.

Table 5. Cumulative mortality of bluegills, fathead minnow larvae, and daphnids after exposure to water from Paiute Diversion Drain diluted with (A) reconstituted water[1] and (B) water from D-Line Canal

Species (and number sampled)	Cumulative mortality of species after tests (percent)					
	Proportion of drain water in sample					NFCRC well-water control[2]
	100 percent	50 percent	25 percent	12.5 percent	0 percent	
A. Drainwater, diluted with reconstituted water						
Bluegills (10)	0	0	10	0	10	0
Fathead minnow larvae (20)	0	0	0	0	0	0
Daphnids (20)	0	0	10	0	5	0
B. Drainwater, diluted with D-Line Canal water						
Bluegills (10)	0	10	10	0	0	0
Fathead minnow larvae (20)	0	0	0	0	0	0
Daphnids (20)	0	10	0	0	0	0

[1] Deionized water reconstituted to the same hardness, alkalinity, specific conductance, and pH as the Paiute Diversion Drain water.

[2] Well water from National Fisheries Contaminant Research Center, Columbia, Mo.

Table 6. Ranges of water-quality measurements in surface-water samples collected daily, August 10-18, 1988, for aquatic toxicity tests[1]

[Abbreviations: NTU, nephelometric turbidity units; ppt, parts per thousand; µS/cm, microsiemens per centimeter at 25°C; µg/L, micrograms per liter; mg/L, milligrams per liter.]

	Paiute Diversion Drain	D-Line Canal	TJ Drain	Hunter Drain	Lead Lake	Stillwater Point Diversion Drain	Stillwater Point Reservoir
Specific Conductance (µS/m)	370-480	350-610	6,100-14,900	410-27,500	5,100-6,100	470-720	1,590-2,510
pH, field (units)	7.5-8.6	8.6-9.4	8.4-8.6	8.0-8.8	8.6-8.9	8.2-8.6	9.0-9.2
Turbidity (NTU)	15-35	3-9	2-8	7-37	37-96	21-54	170-580
Dissolved oxygen (mg/L)	6.8-9.7	9.0-10.3	7.4-10.9	5.6-8.8	5.6-9.2	8.3-9.6	8.2-10
Calcium (mg/L)	31-36	26-32	140-310	32-390	64-74	42-51	22-36
Magnesium (mg/L)	10-13	9-11	160-410	10-250	90-103	12-18	16-21
Hardness (mg/L as $CaCO_3$)	110-140	94-130	1,100-2,500	110-2,300	570-680	140-200	130-170
Sodium (mg/L)	62-84	83-110	1,900-4,700	98-8,600	980-1,100	120-270	310-480
Potassium (mg/L)	2.8-5.4	5.4-9.4	29-57	4.0-210	29-33	7.3-13	15-21
Alkalinity (mg/L as $CaCO_3$)	111-158	113-174	217-319	102-276	227-272	114-312	235-300
Sulfate (mg/L)	52-85	47-130	880-3,600	52-2,900	360-680	110-150	100-240
Chloride (mg/L)	50-70	12-50	2,700-6,200	84-13,000	1,200-1,800	43-63	300-550
Silica (mg/L)	5.8-7.2	5.9-7.6	0.1-3.8	5.0-13	5.1-7.5	11-14	10-12
Salinity (ppt)	0.1-0.3	0-0.5	4.1-13.0	0.0-28	3.1-4.2	0.2-0.8	0.9-1.9
Phosphorus (mg/L)	<0.1-0.2	<0.1	0.4-1.0	<0.1-0.9	0.20-0.37	0.20-0.30	<0.1
Arsenic (µg/L)	10-20	40-50	110-170	20-190	100-130	40-50	80-110
Barium (µg/L)	70-90	40-60	50-110	50-100	110-140	60-70	90-120
Boron (µg/L)	520-760	620-810	6,800-17,000	810-49,000	5,000-6,000	860-1,800	2,000-3,000
Lithium (µg/L)	50-60	50-60	340-760	60-2,300	340-390	60-100	100-130
Mercury (µg/L)	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3
Molybdenum (µg/L)	<20-20	<20-20	270-670	20-1,300	110-130	30-50	50-70
Selenium (µg/L)	<0.3	<0.3	0.9-1.6	<0.3-3.6	<0.3	0.4-0.6	0.4-0.6
Strontium (µg/L)	350-410	340-370	3,200-7,900	390-10,400	1,800-2,000	450-670	520-570
Vanadium (µg/L)	10	10-20	10-20	10-30	20	20	20-30
Zinc (µg/L)	20-70	10-40	10-90	10-90	10-40	40-100	10-50

[1] Analyzed by Environmental Trace Substances Research Center, Columbia, Mo. These water-quality data do not necessarily conform to U.S. Geological Survey guidelines for reporting significant figures.

Table 7. Cumulative mortality of bluegills, fathead minnow larvae, and daphnids exposed to water from TJ Drain diluted with reconstituted water[1]

Species (and number sampled)	Exposure (days)	Cumulative mortality of species in tests (percent)					
		Proportion of drainwater in sample					NFCRC well-water control[2]
		100 percent	50 percent	25 percent	12.5 percent	0 percent	
Bluegills (10)	1	0	0	0	0	0	0
	2	0	0	0	0	0	0
	3	20	20	0	0	0	0
	4	40	30	10	0	0	0
	5	50	30	10	0	0	0
	6	70	30	10	10	0	0
	7	90	50	30	10	0	0
	8	90	50	30	10	0	0
	9	90	70	30	20	0	0
Fathead minnow larvae (20)	1	20	0	0	0	0	0
	2	20	0	0	0	0	0
	3	20	10	0	0	0	0
	4	20	20	10	0	0	0
	5	45	20	10	0	0	0
	6	45	30	20	10	0	0
	7	60	30	20	10	0	0
	8	60	40	20	10	0	0
	9	85	45	20	10	0	0
Daphnids (20)	1	10	0	0	0	0	0
	2	25	0	0	0	0	0
	3	25	20	0	0	0	0
	4	60	30	10	0	0	0
	5	95	30	15	0	0	0
	6	100	40	20	10	0	0
	7		75	25	10	0	0
	8		80	25	10	0	0
	9		100	25	10	0	0

[1] Deionized water reconstituted to the same hardness, alkalinity, specific conductance, and pH as the TJ Drain water.
[2] Well water from National Fisheries Contaminant Research Center, Columbia, Mo.

A dose-response pattern was evident for all species regardless of dilution water. Although the fluctuating salinity was undoubtedly stressful to test organisms, survival of organisms in controls with identical salinity fluctuations strongly suggests that mortalities in drainwater did not result from exposure to salinity alone.

Concentrations of trace elements fluctuated throughout the exposure period, but concentrations of arsenic, boron, lithium, and molybdenum were consistently higher in TJ Drain water than in Paiute Diversion Drain or D-Line Canal water, where no mortality was observed. Levels of arsenic in TJ Drain consistently exceeded 100 µg/L and boron concentrations reached a maximum level of 16,700 µg/L. Concentrations of dissolved selenium ranged from 0.9 to 1.6 µg/L; the highest concentrations were on day 4 when salinity was highest, and the lowest concentrations were on the day of lowest salinity. No mercury was detected in any sample. In addition, aluminum, antimony, beryllium, bismuth, chromium, cobalt, copper, iron, nickel, silver, tin, titanium, thallium, and tungsten did not exceed reporting limits. Ranges of concentrations of other constituents are reported in table 6.

Table 8. Cumulative mortality of bluegills, fathead minnow larvae, and daphnids exposed to water from TJ Drain diluted with water from D-Line Canal

Species (and number sampled)	Exposure (days)	Cumulative mortality of species in tests (percent)					
		Proportion of drainwater in sample					NFCRC well-water control[1]
		100 percent	50 percent	25 percent	12.5 percent	0 percent	
Bluegills (10)	1	0	0	0	0	0	0
	2	0	0	0	0	0	0
	3	20	20	0	0	0	0
	4	40	30	10	0	0	0
	5	50	30	10	0	0	0
	6	70	30	10	10	0	0
	7	90	50	30	10	0	0
	8	90	50	30	10	0	0
	9	90	60	30	20	0	0
Fathead minnow larvae (20)	1	0	0	0	0	0	0
	2	10	0	0	0	0	0
	3	25	10	0	0	0	0
	4	40	15	0	0	0	0
	5	60	20	5	0	0	0
	6	75	40	10	10	0	0
	7	80	40	10	10	0	0
	8	80	40	10	10	0	0
	9	85	40	10	10	0	0
Daphnids (20)	1	0	0	0	0	0	0
	2	0	0	0	0	0	0
	3	35	20	0	0	0	0
	4	60	45	10	0	0	0
	5	100	50	15	0	0	0
	6		70	30	10	0	0
	7		70	30	10	0	0
	8		100	30	10	0	0
	9			30	10	0	0

[1] Well water from National Fisheries Contaminant Research Center, Columbia, Mo.

Well Near TJ Drain

Ground water from the USGS well DH-102B, near TJ Drain (Hoffman and others, table 3), was the most toxic of the water tested. The test was conducted as a static nonrenewal with the one 5-gal sample. Salinity of the ground water was 7.9 ppt and specific conductance was 12,000 µS/cm; the water was tested with bluegills, larval fathead minnows, and daphnids. All organisms exposed to 100-, 50-, 25-, and 12.5-percent ground water died within 24 hours of exposure. No mortality occurred in any controls. The ionic composition and water quality of TJ Drain ground water was different from that of TJ Drain surface water (table 6). The ground water was harder; the calcium level was about two-fold higher than that of the drainwater and was more highly buffered (higher alkalinity). In addition, the pH of the ground water (7.0) was lower than that of the drainwater (8.4-8.6).

Concentrations of arsenic in the ground water (table 9) were higher than in any drainwater tested. Concentrations of lithium and molybdenum were higher in ground water than those measured in TJ Drain surface water. No selenium or mercury was detected in the ground-water sample, but concentrations of boron were high. Survival of freshwater control organisms in the reconstituted water with a salinity of 7.9 ppt indicates that the observed mortality was probably induced by the presence of trace elements in the ground water.

Table 9. Concentrations of inorganic constituents in ground water collected from U.S. Geological Survey well DH-102B in the vicinity of TJ Drain, August 17, 1988[1]

[Except where indicated, all values are in micrograms per liter; mg/L, milligrams per liter.}

Element	Concentration	Element	Concentration
Calcium (mg/L)	544	Iron	<5
Magnesium (mg/L)	268	Lead	<40
Sodium (mg/L)	2,390	Lithium	1,640
Potassium (mg/L)	87	Manganese	1,440
Silica (mg/L)	36.1	Mercury	<0.3
Phosphorus (mg/L)	0.80	Molybdenum	1,150
Aluminum	<30	Nickel	<100
Antimony	<40	Selenium	<0.3
Arsenic	560	Silver	<20
Barium	48	Strontium	13,300
Beryllium	<1	Thallium	<3
Bismuth	<60	Tin	<10
Boron	24,400	Titanium	<20
Cadmium	<2	Tungsten	<2
Chromium	<10	Vanadium	<2
Cobalt	<10	Zinc	57
Copper	<2		

[1] These water-quality data do not necessarily conform to U.S. Geological Survey guidelines for reporting significant figures

Hunter Drain

Hunter Drain water was acutely toxic to all species tested. This was the only water with salinity high enough to allow tests with saltwater species. Neither freshwater nor saltwater organisms survived in treatments of 100-percent or 50-percent drainwater. All species died quickly; 90 percent of the mysids, daphnids, and sheephead minnows died after 48 hours of exposure. After 9 days, at least 40 percent of every species had died in all dilutions (tables 10, 11).

The water quality in Hunter Drain was highly variable (table 6). Salinity ranged from 0 to 28 ppt. The highest salinity was measured on days 3, 4, and 5 under conditions of low flow when there was no visible discharge of irrigation water to the drain. During this 3-day period, the seepage of ground water into Hunter Drain was evident along the banks of the drain. The addition of operational spill water to the drain on day 6 was apparently responsible for the reduction in salinity and conductivity. All the bluegills died on day 4, after 24 hours of exposure to Hunter Drain water when salinity was 28 ppt, which was more than twice as high as on the previous day. Only 10 percent of the fish died on day 4 in other treatments exposed to this level of salinity, but the cumulative mortality of 20 percent in the controls on day 5 is probably related to the high salinity.

Survival, even for one day, of any bluegill at a salinity of 28 ppt was unexpected, based on accepted salt tolerances of the species. The ionic content of water in Hunter Drain and other Stillwater locations differed from that of seawater, which is typically used to estimate salinity tolerances of freshwater organisms. Although the test organisms were apparently more tolerant of salinity with these ionic ratios than of a similar salinity in seawater, it is probable that continued exposure to elevated salinity would have reduced survival in control water. It is unlikely that daily fluctuations in water quality of the magnitude experienced here would be tolerated by the tested species for an extended period.

Table 10. Cumulative mortality of bluegills, fathead minnow larvae, and daphnids exposed to water from Hunter Drain diluted with reconstituted water[1]

Species (and number sampled)	Exposure (days)	Cumulative mortality of species in tests (percent)					
		Proportion of drainwater in sample					NFCRC well-water control[2]
		100 percent	50 percent	25 percent	12.5 percent	0 percent	
Bluegills (10)	1	0	0	0	0	0	0
	2	0	0	0	0	0	0
	3	100	10	10	0	0	0
	4		60	10	10	10	0
	5		80	30	10	20	0
	6		80	30	20	20	0
	7		100	50	20	20	0
	8			60	30	20	0
	9			60	40	20	0
Fathead minnow larvae (20)	1	25	10	0	0	0	0
	2	40	50	0	0	0	0
	3	65	85	0	0	0	0
	4	70	90	20	10	0	0
	5	100	90	30	10	0	0
	6		100	45	25	0	0
	7			60	25	0	0
	8			60	25	0	0
	9			60	40	0	0
Daphnids (20)	1	25	20	0	0	0	0
	2	90	50	0	0	0	0
	3	100	85	0	0	0	0
	4		90	15	10	0	0
	5		90	30	10	10	0
	6		100	50	25	10	0
	7			50	25	10	0
	8			60	25	10	0
	9			75	50	10	0

[1] Deionized water reconstituted to the same hardness, alkalinity, specific conductance, and pH as the Hunter Drain water.
[2] Well water from National Fisheries Contaminant Research Center, Columbia, Mo.

Tests with saltwater species—sheephead minnow larvae and mysid shrimp—were initiated when salinity first exceeded 15 ppt on day 3. Total mortality of both species occurred in the 100-, 50-, and 25-percent dilutions after 7 days of exposure (table 11). The saltwater organisms were exposed under conditions of static renewal during the first 72 hours, but because the salinity of the drainwater decreased to 7 ppt on day 6, testing continued without renewal for the remainder of the 7-day exposure period. Dissolved-oxygen concentrations of the test water exceeded 6.4 mg/L throughout the study and pH ranged from 8.4 to 8.5. Mortality of both species of at least 55 percent occurred in all drain-water dilutions; no mortality occurred in the well-water controls.

Higher levels of trace-element concentrations corresponded with the higher levels of salinity. During days with elevated salinity, concentrations of arsenic in Hunter Drain were similar to those measured in TJ Drain; levels of boron and lithium in Hunter Drain were higher than at any other location, and molybdenum nearly so (table 6). Concentrations of dissolved selenium ranged from below detection limits to 3.6 µg/L and were highest during periods of highest salinity. No mercury was detected in samples from Hunter Drain. In addition, aluminum, antimony, beryllium, bismuth, chromium, cobalt, copper, iron, nickel, silver, tin, titanium, thallium, and tungsten did not exceed reporting limits.

Table 11. Cumulative mortality of saltwater species (sheephead minnow larvae and mysid shrimp) exposed to water from Hunter Drain diluted with reconstituted water[1]

Species (and number sampled)	Exposure (days)	Cumulative mortality of species in tests (percent)					
		Proportion of drainwater in sample					NFCRC well-water control[2]
		100 percent	50 percent	25 percent	12.5 percent	0 percent	
Sheephead minnow larvae (20)	4	60	45	25	20	0	0
	5	90	65	40	35	0	0
	6	100	75	55	40	0	0
	7		100	80	50	0	0
	8			100	55	0	0
	9				55	0	0
Mysid shrimp (20)	4	70	50	20	20	0	0
	5	90	65	35	15	0	0
	6	100	90	50	30	0	0
	7		100	70	55	5	0
	8			100	60	5	0
	9				60	10	0

[1] Deionized water reconstituted to the same hardness, alkalinity, specific conductance, and pH as the Hunter Drain water.
[2] Well water from National Fisheries Contaminant Research Center, Columbia, Mo.

Lead Lake

Water from Lead Lake was moderately toxic to all species tested; the death rate accelerated after 4 days (table 12). Survival rates of bluegill and fathead minnow larvae were similar; the lowest level of effect occurred in the 25-percent dilution. Daphnids were more sensitive to the toxic components in the water than were the fish, and died sooner. No species died in the 12.5-percent dilution or in the controls. Total survival of all organisms in the reconstituted control water, where salinity was similar to that in the Lead Lake water treatments, suggests that salinity alone did not account for the observed mortality.

Reproduction of daphnids was delayed in all treatments. No young were produced by daphnids in any Lead Lake water treatment and there was no evidence of development of a first brood in any individuals examined at the termination of the exposure. Young were produced in both the reconstituted and well-water controls on day 9. Mean number of young per brood in these controls was 8.9 and 9.2, respectively.

Levels of trace elements did not fluctuate markedly throughout the exposure period. Concentrations of selenium and mercury were below analytical reporting levels. In addition, aluminum, antimony, beryllium, bismuth, chromium, cobalt, copper, iron, nickel, silver, tin, titanium, thallium, and tungsten did not exceed reporting limits. Concentrations of arsenic, boron, lithium, and molybdenum were consistently higher in Lead Lake water than in either Paiute Diversion Drain or D-Line Canal, where no mortality was observed. The concentrations of these four trace elements, which were associated with water hardness and specific conductance, appear to be strongly influenced by inflow from TJ Drain. Concentrations of salts in Lead Lake may be naturally increased by evaporative loss, but the addition of water from TJ Drain does not enhance the water quality of Lead Lake.

Table 12. Cumulative mortality of bluegills, fathead minnow larvae, and daphnids exposed to water from Lead Lake diluted with reconstituted water[1]

Species (and number sampled)	Exposure (days)	Cumulative mortality of species in tests (percent)					
		Proportion of drainwater in sample					NFCRC well-water control[2]
		100 percent	50 percent	25 percent	12.5 percent	0 percent	
Bluegills (10)	1	0	0	0	0	0	0
	2	20	0	0	0	0	0
	3	20	0	0	0	0	0
	4	30	0	0	0	0	0
	5	30	20	0	0	0	0
	6	30	20	10	0	0	0
	7	40	20	10	0	0	0
	8	40	30	10	0	0	0
	9	60	30	10	0	0	0
Fathead minnow larvae (20)	1	0	0	0	0	0	0
	2	20	0	0	0	0	0
	3	20	5	5	0	0	0
	4	25	5	5	0	0	0
	5	25	5	10	0	0	0
	6	30	15	10	0	0	0
	7	40	20	10	0	0	0
	8	60	25	15	0	0	0
	9	60	30	15	0	0	0
Daphnids (20)	1	0	0	0	0	0	0
	2	20	0	0	0	0	0
	3	20	5	5	0	0	0
	4	25	5	5	0	0	0
	5	30	15	10	0	0	0
	6	30	15	10	0	0	0
	7	45	30	15	0	0	0
	8	60	35	20	0	0	0
	9	80	45	20	0	0	0

[1] Deionized water reconstituted to the same hardness, alkalinity, specific conductance, and pH as the Lead Lake water.
[2] Well water from National Fisheries Contaminant Research Center, Columbia, Mo.

Stillwater Point Diversion Drain and Stillwater Point Reservoir

Test organisms were differentially sensitive to water from Stillwater Point Diversion Drain. The water was toxic to bluegills and marginally toxic to fathead minnow larvae and daphnids (tables 13 and 14). Mortality occurred after an extended exposure to drainwater; no mortality of any species occurred during the first 3 days of exposure. Bluegill mortality reached 80 percent in undiluted water from Stillwater Point Diversion Drain. In the tests where drainwater was diluted with reconstituted water (table 13), no appreciable mortality occurred in the 12.5-percent dilution, but in tests using water from Stillwater Point Reservoir as a diluent, 20 percent of the fish died in the 12.5 percent dilution (table 14). In controls, no bluegills died in well water, 10 percent died in reconstituted water (table 13), and 20 percent died in Stillwater Point Reservoir water (table 14). Cumulative mortality of fathead minnow larvae and daphnids exposed to Stillwater Point Diversion Drain water diluted with reconstituted water (table 13) was lower than that of bluegills and ranged from 5 to 30 percent. Mortality of fathead minnows and daphnids exposed to Stillwater Point Diversion Drain water diluted with Stillwater

Point Reservoir water (table 14) ranged from 10 to 30 percent and was much lower than bluegill mortality, but generally higher than in tests using reconstituted water (table 13) as a diluent (5-30 percent), but with no clear pattern of dose response. No fathead minnow larvae or daphnids died in the reconstituted or the well-water controls, but in Stillwater Point Reservoir water controls, mortality was 25 percent (table 14).

The range in concentrations of the constituents in Stillwater Point Diversion Drain and Stillwater Point Reservoir remained less variable during the study than those in TJ and Hunter Drains (table 6). The ambient water was well oxygenated and of moderately low specific conductance. Turbidity in Stillwater Point Diversion Drain was similar to Paiute Diversion Drain. Concentrations of constituents also were similar to those found in Paiute Diversion Drain and in D-Line Canal (table 6). Mercury and selenium concentrations in Stillwater Point Diversion Drain were at or below analytical reporting levels. In addition, aluminum, antimony, beryllium, bismuth, chromium, cobalt, copper, iron, nickel, silver, tin, titanium, thallium, and tungsten did not exceed reporting limits.

Table 13. Cumulative mortality of bluegills, fathead minnow larvae, and daphnids exposed to water from Stillwater Point Diversion Drain diluted with reconstituted water[1]

Species (and number sampled)	Exposure (days)	Cumulative mortality of species in tests (percent)					
		Proportion of drainwater in sample					NFCRC well-water control[2]
		100 percent	50 percent	25 percent	12.5 percent	0 percent	
Bluegills (10)	1	0	0	0	0	0	0
	2	0	0	0	0	0	0
	3	0	0	0	0	0	0
	4	20	20	10	0	0	0
	5	40	30	20	0	0	0
	6	40	30	20	10	0	0
	7	40	30	20	10	10	0
	8	60	30	20	10	10	0
	9	80	40	20	10	10	0
Fathead minnow larvae (20)	1	0	0	0	0	0	0
	2	0	0	0	0	0	0
	3	0	0	0	0	0	0
	4	5	0	10	0	0	0
	5	5	5	10	0	0	0
	6	10	10	10	0	0	0
	7	10	10	10	0	0	0
	8	15	10	10	5	0	0
	9	30	10	10	5	0	0
Daphnids (20)	1	0	0	0	0	0	0
	2	0	0	0	0	0	0
	3	0	0	0	0	0	0
	4	0	0	10	0	0	0
	5	10	10	10	0	0	0
	6	10	10	10	0	0	0
	7	15	10	10	0	0	0
	8	15	10	10	5	0	0
	9	25	10	10	5	0	0

[1] Deionized water reconstituted to the same hardness, alkalinity, specific conductance, and pH as the Stillwater Point Diversion Drain water.

[2] Well water from National Fisheries Contaminant Research Center, Columbia, Mo.

Table 14. Cumulative mortality of bluegills, fathead minnow larvae, and daphnids exposed to water from Stillwater Point Diversion Drain diluted with water from Stillwater Point Reservoir

Species (and number sampled)	Exposure (days)	Cumulative mortality of species in tests (percent)					
		Proportion of drainwater in sample					NFCRC well-water control[1]
		100 percent	50 percent	25 percent	12.5 percent	0 percent	
Bluegills (10)	1	0	0	0	0	0	0
	2	0	0	0	0	0	0
	3	0	0	0	0	0	0
	4	30	20	10	0	0	0
	5	60	20	10	0	0	0
	6	60	20	10	0	0	0
	7	60	20	10	10	0	0
	8	70	30	20	10	10	0
	9	80	40	20	20	20	0
Fathead minnow larvae (20)	1	0	0	0	0	0	0
	2	0	0	0	0	5	0
	3	0	0	0	0	10	0
	4	10	15	10	0	10	0
	5	10	15	15	10	10	0
	6	15	20	15	10	15	0
	7	20	20	15	10	20	0
	8	25	20	15	15	20	0
	9	30	25	20	25	25	0
Daphnids (20)	1	0	0	0	0	0	0
	2	0	0	0	0	5	0
	3	0	0	0	0	5	0
	4	10	20	10	0	10	0
	5	10	20	10	0	10	0
	6	15	20	10	0	20	0
	7	25	20	10	0	20	0
	8	25	20	10	0	25	0
	9	25	25	20	20	25	0

[1] Well water from National Fisheries Contaminant Research Center, Columbia, Mo.

Because mortality in water from Stillwater Point Diversion Drain was higher than in apparently similar water from Paiute Diversion Drain and D-Line Canal, water samples from all drain sites were collected August 17, 1988, for chemical analysis of manmade organic constituents. No organic constituent was found at concentrations that might be expected to cause adverse effects on the test organisms. Consistent levels of phenols (2.6-5.4 µg/L) were detected in every sample, which suggests incidental contamination during sample collection or chemical analysis. Results from these analyses did not explain the mortality observed in Stillwater Point Diversion Drain water.

Mortality in undiluted water from Stillwater Point Reservoir was low, but consistent (20-25 percent). No substantial mortality of any species occurred in dilutions of Stillwater Point Reservoir water. Daphnids reproduced equally in all treatments on day 9, with the mean number of young per brood ranging from 8.0 to 9.5. The reservoir water was turbid, ranging from 168 to 580 NTU's, which may have stressed the test organisms in the 100-percent treatment. Concentrations of boron, lithium, and molybdenum in the reservoir (table 6) were generally similar to those in Stillwater Point Diversion Drain water. Concentrations of arsenic were only slightly lower than those in Lead Lake and TJ Drain and may have contributed to the observed mortality. Arsenic concentrations in the reservoir were approximately twice those in Stillwater Point Diversion Drain.

EFFECT OF IRRIGATION DRAINAGE ON AQUATIC ORGANISMS

Water from Hunter and TJ Drains and ground water from the well near TJ Drain was acutely toxic to all species tested (fig. 5). On the basis of effects of the drainwater on cumulative mortality and daphnid reproduction, the "No Observed Effect Concentration" (NOEC)[1] for both Hunter and TJ Drains was less than 12.5 percent drainwater. Lead Lake water was moderately toxic to all species tested, with an NOEC of 25 percent drainwater for both fish species and an NOEC of less than 12.5 percent for daphnids. In tests with Stillwater Point Diversion Drain water diluted with Stillwater Point Reservoir water, where mortality occurred in every treatment, an NOEC was not established, but in tests with Stillwater Point Diversion Drain water diluted with reconstituted water, the NOEC was 25 percent for daphnids and fathead minnows and 12.5 percent for bluegill. Water samples from Paiute Diversion Drain and D-Line Canal were not toxic to the species tested.

[1]A time-independent measure that describes the threshold concentration below which predefined effects are not observed.

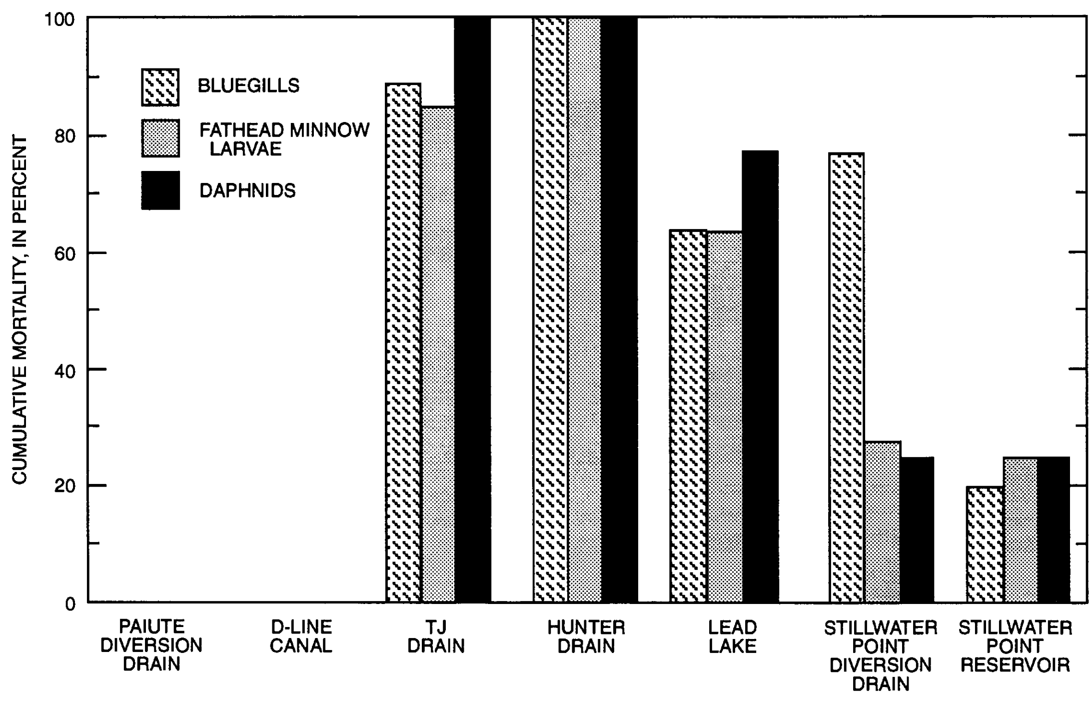

Figure 5. Cumulative mortality of freshwater organisms in undiluted surface-water samples collected in and near Stillwater Wildlife Management Area, August 1988. Data for Paiute Diversion Drain and D-Line Canal showed no mortality.

In both Hunter and TJ drains, dramatic daily fluctuations in water quality were measured, and specific conductance ranged from 410 to 27,500 μS/cm (about 270 to 17,900 mg/L dissolved solids) in Hunter Drain and from 6,100 to 14,900 μS/cm (about 4,000 to 9,700 mg/L dissolved solids) in TJ Drain (fig. 6). Control organisms in reconstituted water, where conductance was similar to that of the drainwater, survived exposure to daily fluctuations of similar magnitudes. Saltwater organisms, sheephead minnow larvae and mysids, did not survive in Hunter Drain water although the salinity was within their range of tolerance.

A dose-response relationship was evident in TJ drainwater when diluted with reconstituted water of a similar salinity and when salinity was decreased by dilution with water from D-Line Canal. From 85 to 100 percent of the organisms died in Lead Lake water; controls with similar specific conductance (that is, salinity) showed no mortality. Although the elevated salinity in tests with drainwater from both locations undoubtedly stressed the organisms, the results suggest that salinity alone does not account for the mortality observed.

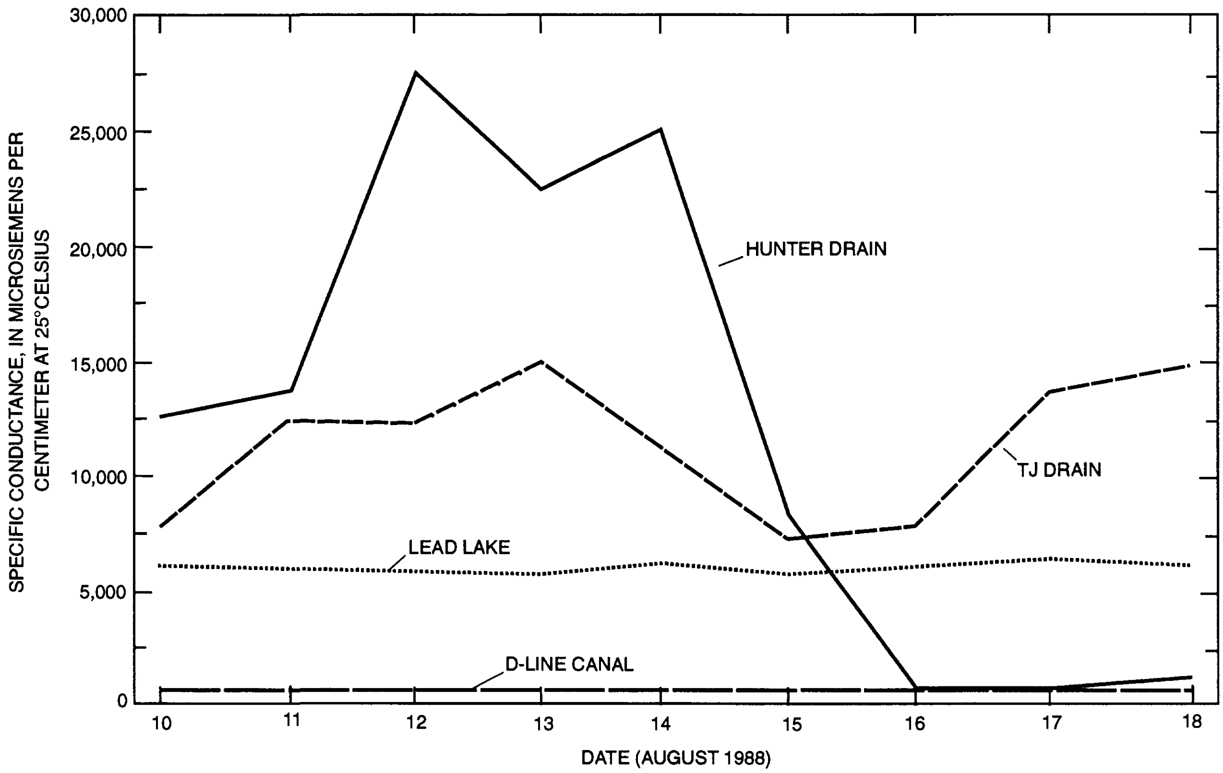

Figure 6. Changes in specific conductance in Lead lake and selected drains during toxicity study, August 10-18, 1988.

In general, higher concentrations of trace elements corresponded to higher levels of specific conductance (fig. 7). In addition, subjective comparison of cumulative mortalities and concentrations of trace elements at each location suggested that the concentrations or arsenic, boron, lithium, and molybdenum were higher at locations where appreciable mortality occurred. No single trace element was present in concentrations that were acutely toxic to the species tested (U.S. Environmental Protection Agency, 1986); therefore, the toxicity is attributed to the interactive effects of the aggregate trace elements present. This conclusion is supported by the results of Dwyer and others (1990, p. 18) who exposed striped bass (*Morone saxatilis*) to these elements and also to copper and strontium, both by single element and in combination. Individually, these six elements were not acutely toxic to the bass in the concentrations found at Stillwater WMA, but in aggregate were acutely toxic.

Ionic Composition

In assessing the hazard to aquatic organisms, the ionic composition of the water should also be considered. For example, in a study subsequent to this one that used striped bass in water reconstituted to resemble Pintail Bay in Stillwater WMA, Dwyer and others (1990, 1992) concluded that the unusually low hardness of this saline water did not diminish toxicity of the combined trace elements—arsenic, boron, copper, lithium, molybdenum, and strontium.

In the present study, water from the shallow well near TJ Drain was acutely toxic to bluegills, larval fathead minnows, and daphnids. This ground water was classified as hard, with the calcium concentration about two-fold higher than the nearby TJ Drain water. Mortality is attributed primarily to a combination of toxic trace elements regardless of the benefit of increased hardness. In follow-up work by Dwyer and others (1990, p. 26), using water from five additional wells in and near Stillwater WMA, acute toxicity to striped bass—a salt tolerant species—was demonstrated.

Thus, salinity alone may not explain the mortality observed in certain drainwater, but rather a mixture of trace elements and atypical ion ratios (compared to seawater; Ingersoll and others, 1992).

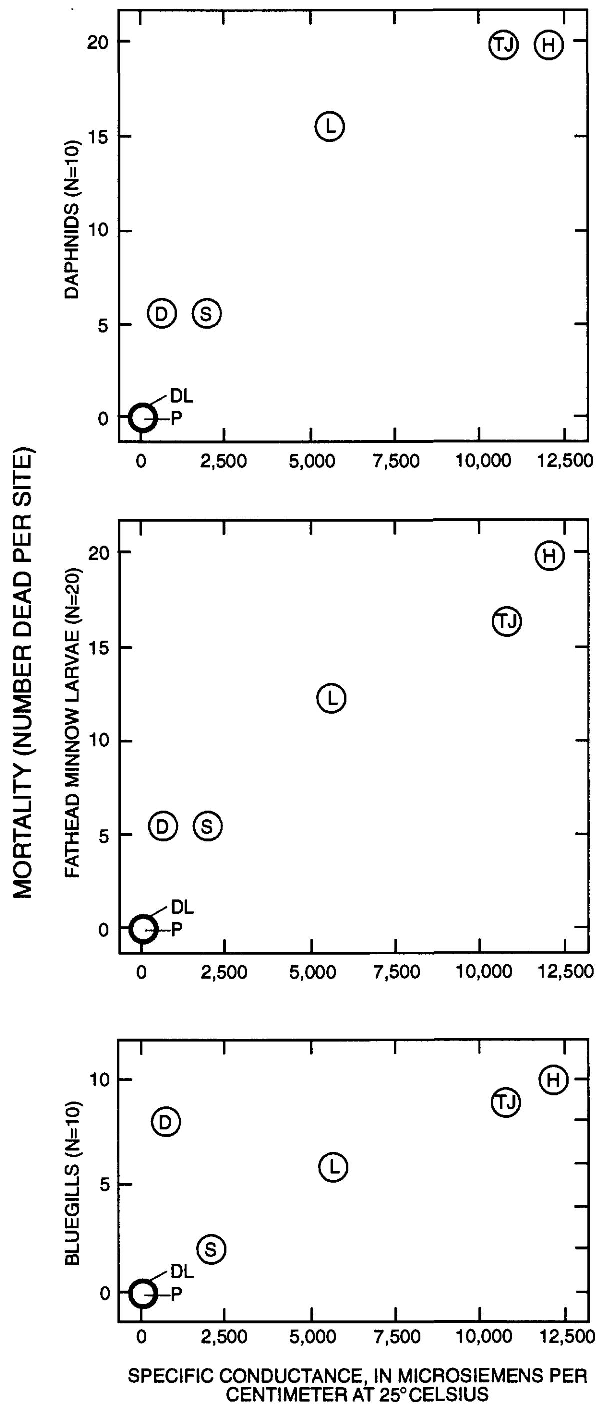

Figure 7. Relations between specific conductance and mortality of bluegills (r=0.88), fathead minnow larvae (r=0.93), and daphnids (r=0.97) for water from Paiute Diversion Drain (P), D-Line Canal (DL), TJ Drain (TJ), Hunter Drain (H), Lead Lake (L), Stillwater Point Diversion Drain (D), and Stillwater Point Reservoir (S).

(p. 39 follows)

BIOLOGICAL PATHWAYS: MOVEMENT OF SELENIUM AND MERCURY

Some potentially toxic trace elements in irrigation drainage are known to biomagnify up the foot chain, thus affecting wildlife of an area, particularly waterfowl. Selenium and mercury are important trace elements in the study area and both are known to biomagnify.

STUDY AREAS

Three areas were selected for in-depth study of biological pathways: TJ Drain/Lead Lake and Hunter Drain/Goose Lake systems in Stillwater WMA (fig. 8), and A-Drain and ponds of the Fernley WMA (fig. 9). These lakes and ponds include emergent wetlands and are managed with water-control structures. Additional samples were collected from other wetlands and from irrigation drains throughout the Fallon agricultural area of the Newlands Irrigation Project area (table 15, fig. 10) to provide a broader scope of the extent of high selenium and mercury concentrations.

Lead Lake, which has three major water sources, is the most hydrologically complex of the areas. It is a 1,000-acre, initial wetland unit that receives irrigation drainage directly before much of the water evaporates and constituents become concentrated; therefore, its water quality is commonly better than that in the connecting wetlands downgradient. However, Lead Lake has a history of avian botulism and unexplained fish and migratory bird deaths, and most of the emergent vegetation has perished in the last 30 years. Selenium was found in the headwaters of the recently constructed (1982-1983) TJ Drain, which ultimately discharges into Lead Lake (U.S. Bureau of Reclamation, 1987, p. B14). Selenium accumulation in juvenile migratory birds from Lead Lake was documented by Hoffman and others (1990, p. 67).

Hunter Drain was included in the pathways study because refuge biologists had noted exceptionally high specific conductance (Steven P. Thompson, U.S. Fish and Wildlife Service, oral commun., 1988) and selenium concentrations above effect level in some juvenile birds from Goose Lake, at the drain terminus (Hoffman and others, 1990, p. 66). This 9-mile drain, which serves only about 180 acres of irrigated land, is a relatively simple flow system. Discharge is typically less than 1 ft^3/s, but operational releases occasionally cause flow peaks of relatively fresh water.

Fernley WMA, near Stillwater WMA, was studied because selenium in livers of juvenile migratory birds exceeded effect levels (Hoffman and others, 1990, p. 67). About 40 percent of the inflow is ground water from Truckee Canal seepage (Van Denburgh and Arteaga, 1985, p. 6), which passes through the same ancient lake-bed sediments as does the drainage from the Stillwater Wildlife Management Area. Most of the water enters the wetlands through A-Drain (from irrigation drainage) and discharges into South Pond, then into a series of connecting ponds (fig. 9).

Most of the additional samples for selenium and mercury were collected principally from drains throughout the irrigation area—about 60,300 acres served by about 350 mi of drainage ditches. Sites were selected to represent, approximately, each 1- to 2-mi^2 area of irrigated land in the study area. These sites are shown in fig. 10 and listed in table 15.

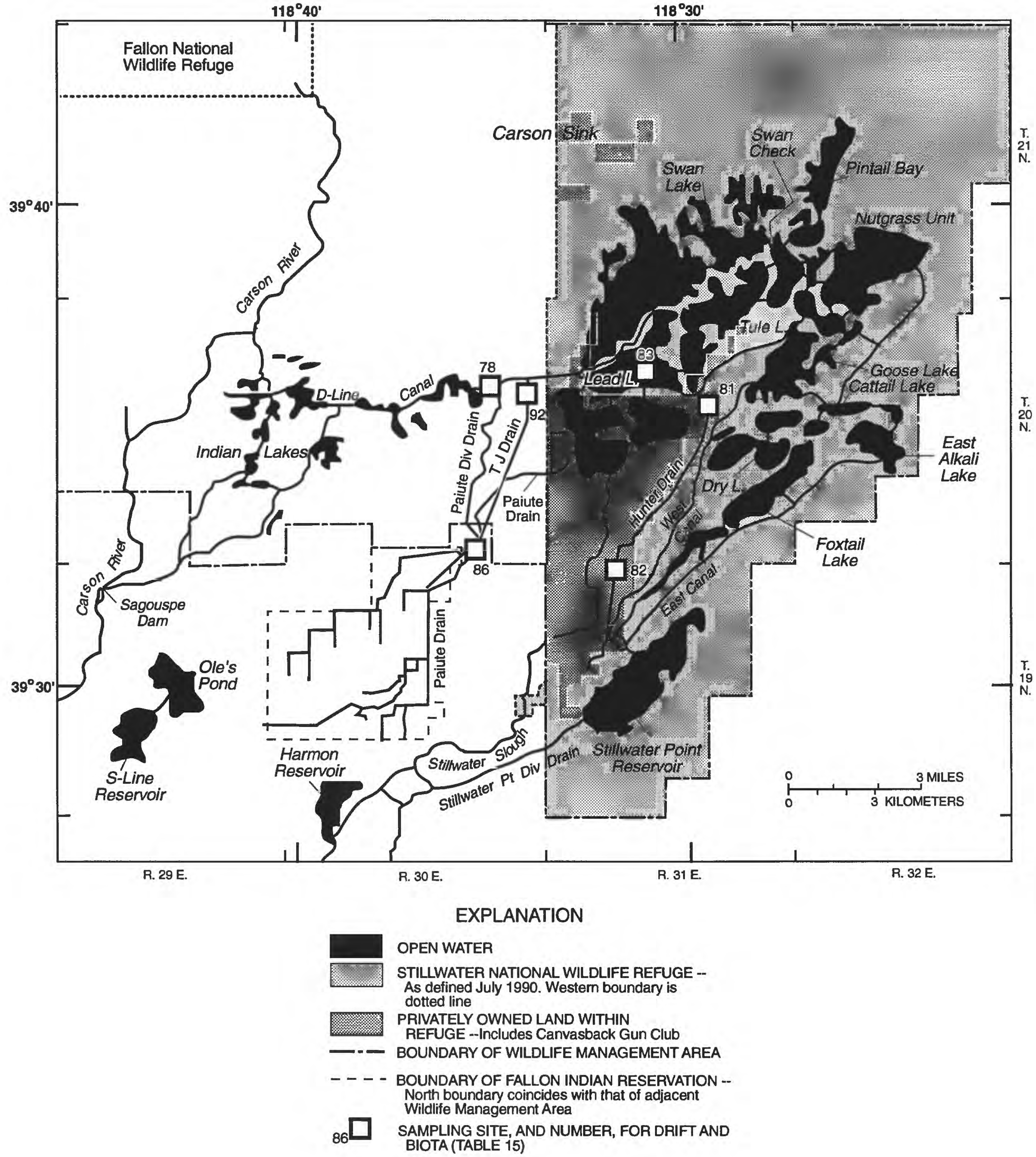

Figure 8. Location of sampling sites for drift and biota in and near Stillwater Wildlife Management Area. Sites are listed in table 15. (Map modified from Lico, 1992.)

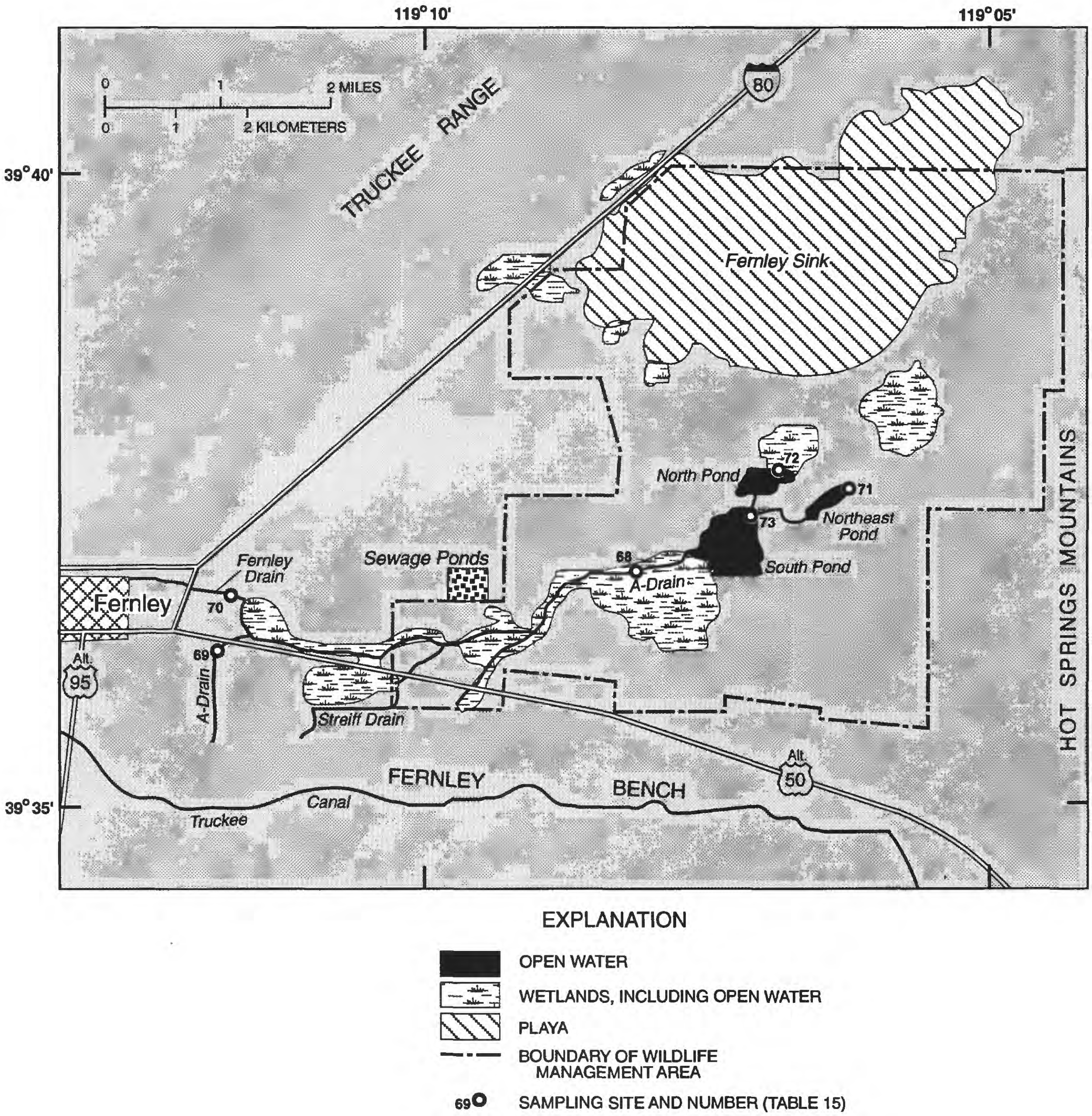

Figure 9. Location of sampling sites for drift and biota in and near Fernley Wildlife Management Area. Sites are listed in table 15. (Map modified from Lico, 1992.)

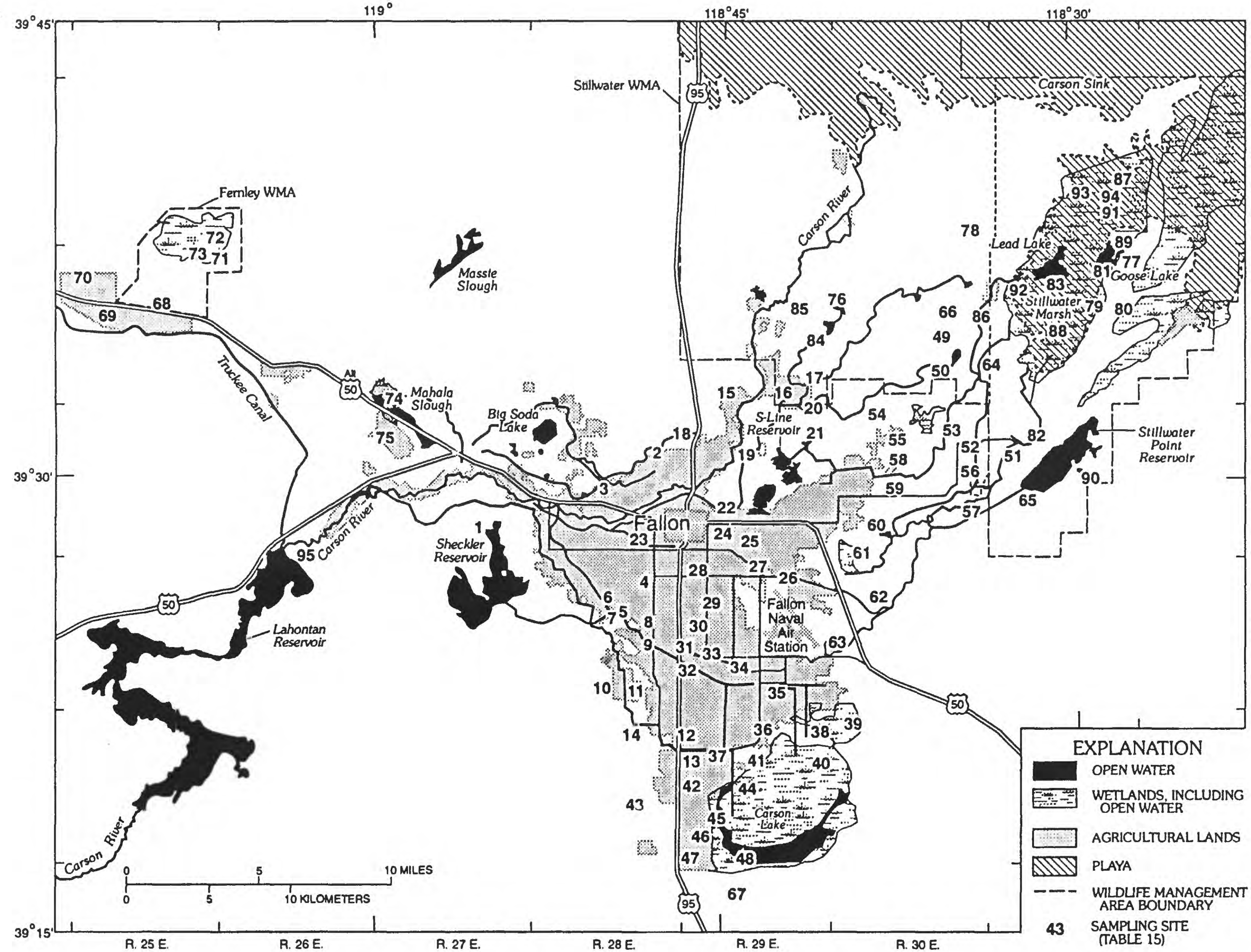

Figure 10. Location of additional sampling sites for detritus and algae in and near Stillwater and Fernley Wildlife Management Areas and Carson Lake. Site names are listed in table 15. (Map modified from Seiler and Allander, in press.)

Table 15. Sampling sites for drift, detritus, and algae

[Locations are shown in figures 8, 9, and 10; data were published by Rowe and others (1991, tables 20, 21)]

Fallon agricultural area

2. Old Reservoir
3. Soda Lake Drain
4. Upper L Drain
5. South Carson River Drain
6. Sheckler Deep Drain
7. Upper West Side Drain
8. Upper Diagonal 2 Drain
9. Upper Diagonal Drain
10. Gummow Drain
11. Carson Lake I Extension Drain
12. Carson Lake Drain
13. Carson Lake 1A Drain
14. A1 Drain
15. Mussi Drain
16. F2 Drain
17. Shaffner Drain
18. ERB Drain
19. Lower Soda Lake Drain
20. Paiute Extension Branch 1 Drain
21. Harmon I Deep Drain
22. S-Line Reservoir
23. New River Extension Drain
24. Upper Harmon Deep Drain
25. Harmon 2 Drain
26. New River Drain
27. Upper New River Drain
28. LD Drain
29. Mid L Drain
30. L3 Drain
31. L2 Drain
32. Upper Diagonal Drain[1]
33. Middle L Drain
34. LB Drain
35. L Branch 1 Deep Drain
36. Lower L Drain
37. Mid Carson Lake Drain
38. A-Line Canal
39. Pierson Drain
40. J1 Deep Drain
41. Yarbrough Drain
42. Carson Lake Branch 3 Drain
43. Carson Lake Branch 1 Drain
44. Downs Drain
54. R2 Drain
55. Upper Paiute Drain
58. Harmon Deep Drain
59. S2G Drain
60. Harmon Reservoir
61. S1B Drain
62. Lower Diagonal 1 Drain
63. Lower Diagonal Drain

Carson Lake area

45. Lower Carson Lake Drain
46. Holmes Branch 2 Drain
47. Holmes Drain
48. NE Carson Lake
67. Carson Lake, Sprig Pond

Stillwater Wildlife Management Area

49. Patrick Drain
50. Kent Lake Extension Drain
51. Lower Stillwater Slough
52. Paiute Branch 3 Drain
53. S1 Deep Drain
56. S2C Drain
57. Upper Stillwater Slough
64. Paiute Branch 1 Drain
65. Stillwater Point Reservoir
66. Upper TJ Drain
76. Big Indian Lake
77. Cattail Lake
78. D-Line Canal
79. Dry Lake East
80. Dry Lake West
81. Hunter Drain
82. Hunter Drain South[1]
83. Lead Lake
84. Likes Lake
85. Papoose Lake
86. Paiute Drain
87. Pintail Bay
88. South Lead Lake
89. South Nutgrass
90. Stillwater Point Reservoir
91. Swan Lake Check
92. TJ Drain
93. Tule Lake
94. West Nutgrass

Fernley Wildlife Management Area

68. Lower A-Drain[1]
69. Upper A-Drain[1]
70. Fernley drain, west
71. Fernley WMA, East Pond
72. Fernley WMA, North Pond
73. Fernley WMA, South Pond

Background and other sites

1. Sheckler Reservoir
74. North Mahala Slough
75. South Mahala Slough
95. Carson River Below Lahontan

[1] Some sites were mislabeled in tables 20 and 21 of Rowe and others (1991): Site 32, Upper Diagonal Drain (sample number 88926), was mislabeled as site 63, Lower Diagonal Drain; site 82, Hunter Drain South (sample 89058), was mislabeled as site 81; site 68, Lower A-Drain (samples 89067 and 89202), was mislabeled as Fernley Drain; and site 69, Upper A-Drain (sample 88171), was mislabeled as Fernley South Drain.

APPROACH AND METHODS

On the basis of the findings of Hoffman and others (1990) that concentrations of selenium and mercury in filtered water samples were low, it was thought that selenium, and possibly mercury, were moving through biological pathways and that transport was through organic rather than inorganic forms. No uniform set of plants or animals was found in all study sites, and living organisms were not always available; therefore, organically rich detritus was sampled to provide continuity throughout the study areas. Because it is lightweight, detritus transports easily down irrigation drainage ditches through routine operational releases and other peak flows. Living plant material, principally filamentous algae, and drift also were collected where available. Definitions of detritus and drift and the sampling procedures used are described by Rowe and others (1991, p. 11-13).

Qualitative analysis of the digestive tracts in birds was made to verify that organisms included in trace-element analysis were indeed diet items of migratory birds. The birds were primarily coots (*Fulica americana*), black-necked stilts (*Himantopus mexicanus*), and avocets (*Recurvirostra americana*), but ducks also were examined. The extent of digestion of the gut contents was a major variable because the elapsed time between collection and preservation varied widely.

A one-time estimate of the standing crop of vegetation (filamentous algae and submergent vascular plants) throughout the TJ Drain system was made August 27, 1990. The drain was divided into 1.0-mi segments, and the width of the drain was measured at 0.5-mi intervals. Transects were made at the midpoint of each segment as determined by measuring with a vehicle odometer. The transects consisted of either three or five evenly spaced sample sites across the width of the drain. Five samples were collected where drain width exceeded 10 ft. A Surber square-foot sampler was used to define the individual sample area. The attached net captured the vegetation after it was severed by the investigator and released into the current. Composite plant samples were frozen in 1-gal jars. Samples were later thawed, hand rinsed, drained, and weighed wet. Dry weights were obtained by drying in an oven at 104°C until weight remained constant.

To determine the source areas of selenium and mercury, sample points were selected throughout the drainage system in such a way that each point represented drainage from about a 1-2-mi^2 area of irrigated land. From these sites, organic detritus and filamentous algae, if present, were collected and analyzed. Although many of the managed wetland units were dry because of the drought, the wetlands sampled contained water. To identify source areas where selenium and mercury are most available biologically, the data sets for both detritus and filamentous algae were displayed through a geographic-information system.

RESULTS

Examination of the upper digestive tracts of 66 migratory birds from Carson Lake and Stillwater WMA confirmed that algae, vegetation, mixed drift, and insects were consumed by migratory birds in the study area. Content of the digestive tracts varied considerably between species and between individuals of the same species. Leeches (*hirunids*), ostracods, and daphnids (*Daphnia magna*) found in drift were not found in gut contents, but these relatively soft-bodied organisms may have been fragmented in the gizzard and therefore difficult to identify. Seeds of emergent vascular plants were found in digestive tracts of ducks. Digestive tracts of 11 black-necked stilts were examined and found to contain primarily water boatmen (*corixids*). No adult brine flies (*Diptera*)were found in the black-necked stilt digestive tracts examined, but stilts have been observed feeding heavily on brine flies at times in Hunter Drain (Steven P. Thompson, Stillwater WMA, U.S. Fish and Wildlife Service, oral commun., 1988).

Because plant material dominated the biomass in the drains and wetlands, detritus was assumed to be primarily of plant origin, with associated microorganisms, and did indeed contain recognizable plant and animal parts. Organically rich sediment, varying in depths at the soil-water interface, was the lightest fraction of the bottom sediment (typically 85-90 percent water). Because of its light-brown color, detritus appeared to be oxygenated and in chemical contact with the water column. Detritus was in direct contact with the most abundant benthic insect larvae in the study areas, midge (*Chironomus sp.*) and brine flies; invertebrates were not typically found in anaerobic sediments below the detrital layers at the sampled locations. All data collected were reported by either Hoffman and others (1990) or Rowe and others (1991).

Detritus sampling was a significant factor in establishing the biological pathways by which selenium and mercury moved into wildlife. A total of 112 composite detritus samples from all sites were analyzed. The concentrations of selenium and mercury, respectively, ranged from <0.09 to 8.04 and from <0.04 to 97.8 µg/g, dry weight.

Exceptionally high concentrations of mercury (26-98 µg/g) were found in three detritus samples from Indian Lakes within Stillwater WMA and from ten irrigation-drain samples. Long and Morgan (1990, p. 41) suggest that concentrations greater than or equal to 1.0 µg/g mercury, dry weight, in sediment would adversely affect exposed invertebrates. This criterion was exceeded in 47 of 112 (42 percent) of the detritus samples analyzed (Rowe and others, 1991).

Lemly and Smith (1987, p. 9) predicted reproductive failure or mortality in fish and waterfowl exposed to sediment containing selenium concentrations greater or equal to 4.0 µg/g, dry weight, because of food-chain bioaccumulation. This criterion was exceeded in only 4 of the 112 detritus samples (4 percent); 3 of those were from Fernley WMA.

Filamentous algae were not present at all detritus sampling sites. The concentrations of mercury and selenium in 87 algae samples ranged from <0.02 to 10.4 and from <0.06 to 5.6 µg/g, dry weight, respectively. The criteria used to evaluate mercury and selenium concentrations in algae are based on dietary bioaccumulation in fish and birds. The effect criterion for mercury in bird diets is 0.39 µg/g, dry weight (Heinz, 1979, p. 395; Hoffman and others, 1990, p. 26), and for selenium in fish diet is 5.0 µg/g, dry weight (Lemly and Smith, 1987, p. 9) The mercury criterion was exceeded in 49 of 87 (56 percent) filamentous algae samples. The selenium criterion was exceeded in only two samples.

Samples of drift were taken for qualitative biological pathway evaluations. The rates of drift movement were not quantified and the data are qualitative. Most of the 55 samples were taken from the Lead Lake, Fernley WMA, and Hunter Drain systems. Sample contents and volumes were highly variable between sites and within sites sampled at various times, but most macroinvertebrates and aquatic plants were in drift. The exception—emergent aquatic plants—were not identified in drift, but may have contributed to the undifferentiated detritus parts. Dominant parts of drift included algae, submergent vascular plants, detritus, daphnids, ostracods, amphipods (*Gammarus sp.*), corixids, chironomids, brine flies, leeches, and odonates.

Selenium was detected in most drift samples, with the highest concentration (10.0 µg/g, dry weight) found in daphnids from South Pond in Fernley WMA. Eight of the 55 (15 percent) samples contained concentrations of selenium greater than the 5.0 µg/g dietary criterion that has been shown to cause reproductive failure or mortality in fish through food-chain bioconcentration (Lemly and Smith, 1987, p. 9). Concentrations in seven of these samples were greater than 7.0 µg/g, dry weight. This concentration in the diet also may cause reproductive failure or mortality in some migratory birds (G.J. Smith, U.S. Fish and Wildlife Service, oral commun., 1989).

Although no attempt was made to establish contaminant loading estimates in aquatic drift, a one-time estimate of the standing crop of all vegetation in TJ drain was made August 27, 1990. The instantaneous standing crop of vegetation in the 17-mi-long TJ Drain was about 15,500 kg (17 tons), dry weight. Using the selenium concentration range of 0.61-2.1 µg/g for vegetation, there was at that time between 9.5 and 31.9 g of selenium fixed in vegetation. This estimate was made several days after a high discharge event when there was visual evidence that large quantities of algae and vascular plants had recently been flushed downstream. Selenium is also found in invertebrates and other animals and in detrital matter, but no attempt was made to estimate the standing crop of these groups because little remained after the discharge.

Brine fly adults were sampled where available. Six of the twelve samples (50 percent) contained selenium in excess of the 7.0 µg/g, dry weight, dietary criterion for birds (G.J. Smith, U.S. Fish and Wildlife Service, oral commun., 1989).

Bioaccumulation and Biomagnification of Selenium and Mercury

Selenium concentrations in filtered water samples from the general study area, including the lower TJ Drain and Lead Lake, were at or below the analytical reporting limit of 1.0 µg/L (Hoffman and others, 1990, p. 77). Higher selenium concentrations, as much as 46 µg/L, were found in filtered sample water from the headwaters of the TJ Drain system (Tokunaga and Benson, 1991, p. 20, 28). Similarly, in California at the Grasslands Water District and Kesterson National Wildlife Refuge, dissolved selenium was quickly absorbed into biota, primarily plants, resulting in low concentrations in water (Presser and Ohlendorf, 1987, p. 811, 815).

Selenium and mercury are not homogeneously distributed in the water or surficial soils within the study area (U.S. Bureau of Reclamation, 1987, p. B14; Ronald R. Tidball, U.S. Geological Survey, oral commun., 1989). Selenium concentrations in water are not a reliable indicator of the magnitude of contamination of selenium in organic matter (Hoffman and others, 1990, p. 77). Evidence of bioaccumulation of mercury in biota was found where dissolved mercury concentrations in water were below the analytical reporting limit (1990, p. 36, 60).

Both selenium and mercury are known to bioaccumulate in detritus. Lemly and Smith (1987, p. 5) discussed the potential importance of detritus pathways leading to fish and migratory birds in situations where selenium may not be detectable in water. Depending on waterway morphology and flow, detritus may accumulate and be available to consumers for several years.

Maximum observed concentrations of selenium and mercury in detritus were 8 and 98 µg/g, dry weight, respectively. Sites with high selenium concentrations in detritus correlate with sites where Hoffman and others (1990, p. 67-70) found high selenium concentrations in juvenile bird livers and muscle. The highest mercury concentration found in detritus was from Indian Lakes, which corresponds to data from Cooper and others (1985, p. 57) that showed elevated mercury concentrations in fish and fish fillets from Indian Lakes. Detritus appears to be a useful medium with which to qualitatively assess the spatial distribution of biologically available selenium and mercury.

Filamentous algae and vascular aquatic plants also may bioaccumulate selenium (Presser and Ohlendorf, 1987, p. 811; Lemly and Smith, 1987, p. 4) or mercury (Eisler, 1987, p. 21), or selenium and mercury (Hoffman and others, 1990, p. 62). In this study, concentrations of selenium and mercury in algae were similar to those in detritus at the same locations. Algae were widespread and nearly as useful as detritus in understanding the dynamics of selenium and mercury movement in irrigation drains and wetlands.

Biomagnification of selenium was documented in juvenile black-necked stilts from Lead Lake (Hoffman and others, 1990, p. 67). Data from the following section on waterfowl production show that selenium concentrations in juvenile bird (cinnamon teal [*Anas cyanoptera*] and coot) tissues were greater than 10,000 times those found in water, and that some migratory birds had accumulated selenium to levels at which mortality or reproductive impairment would be expected.

In the Stillwater study area, bioaccumulation appeared to occur primarily in the irrigation drains. Biomagnification also occurred in drains, but was more evident in the initial wetlands, as was the situation in Grasslands Water District, California, where the largest concentrations of selenium were found in animal tissue collected in the initial wetlands to receive selenium-bearing water (Presser and Ohlendorf, 1987, p. 815).

Selenium and Mercury Pathways

Algae and other aquatic vegetation have been observed moving down the drains. Much of this movement appears to be associated with peak discharges resulting from operational spills or heavy rainfall. Assessments of the vegetation standing crops in TJ Drain followed a large storm that apparently had flushed large quantities of vegetation downstream to Lead Lake. About 15,500 kg, dry weight, of vegetation remained.

The biological components actually being transported were isolated in the drift samples. The irregular mixture of vegetation and invertebrates in these samples makes the data appropriate only for qualitative evaluation. Analysis of drift samples indicates that selenium was being bioaccumulated in plants, biomagnified in invertebrates, and that both components in drift and detritus were transported to wetlands by drain flow.

Figure 11 illustrates the flow path of selenium in particulate matter to downgradient wetlands. The TJ Drain appears to be the largest contributor of selenium to Lead Lake. Paiute Diversion Drain seasonally supports large biomasses of algae and vascular plants, which also may be an important source of selenium to Lead Lake. Biological samples from wetland sites downgradient of Lead Lake, which are maintained by Lead Lake water, were generally lower in selenium than those from Lead Lake.

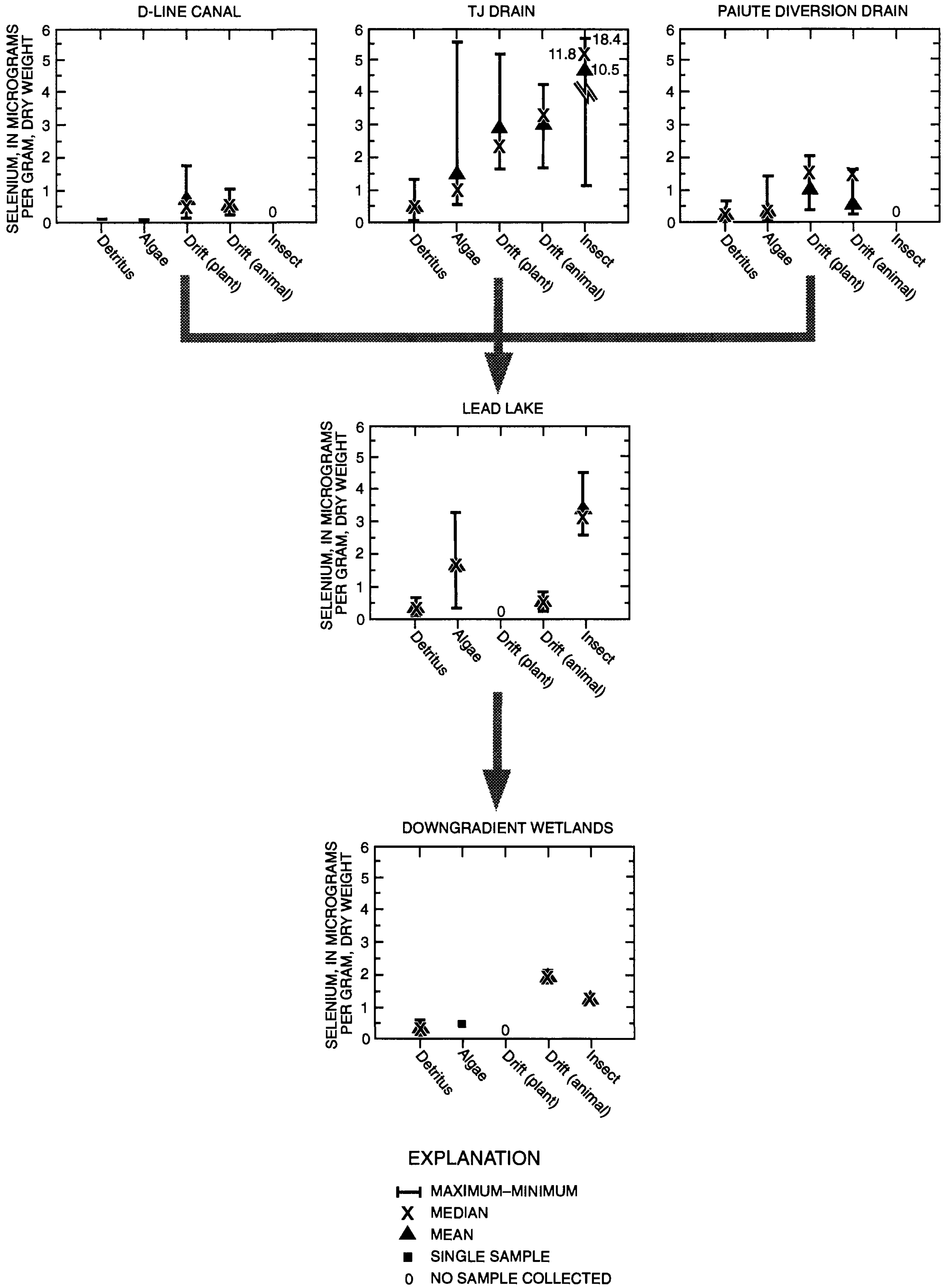

Figure 11. Generalized flow path in Stillwater Wildlife Management Area and selenium concentrations in composite samples from input drains, Lead Lake, and downgradient wetlands. Data from Hoffman and others (1990, table 19) and Rowe and others (1991, tables 20 and 21).

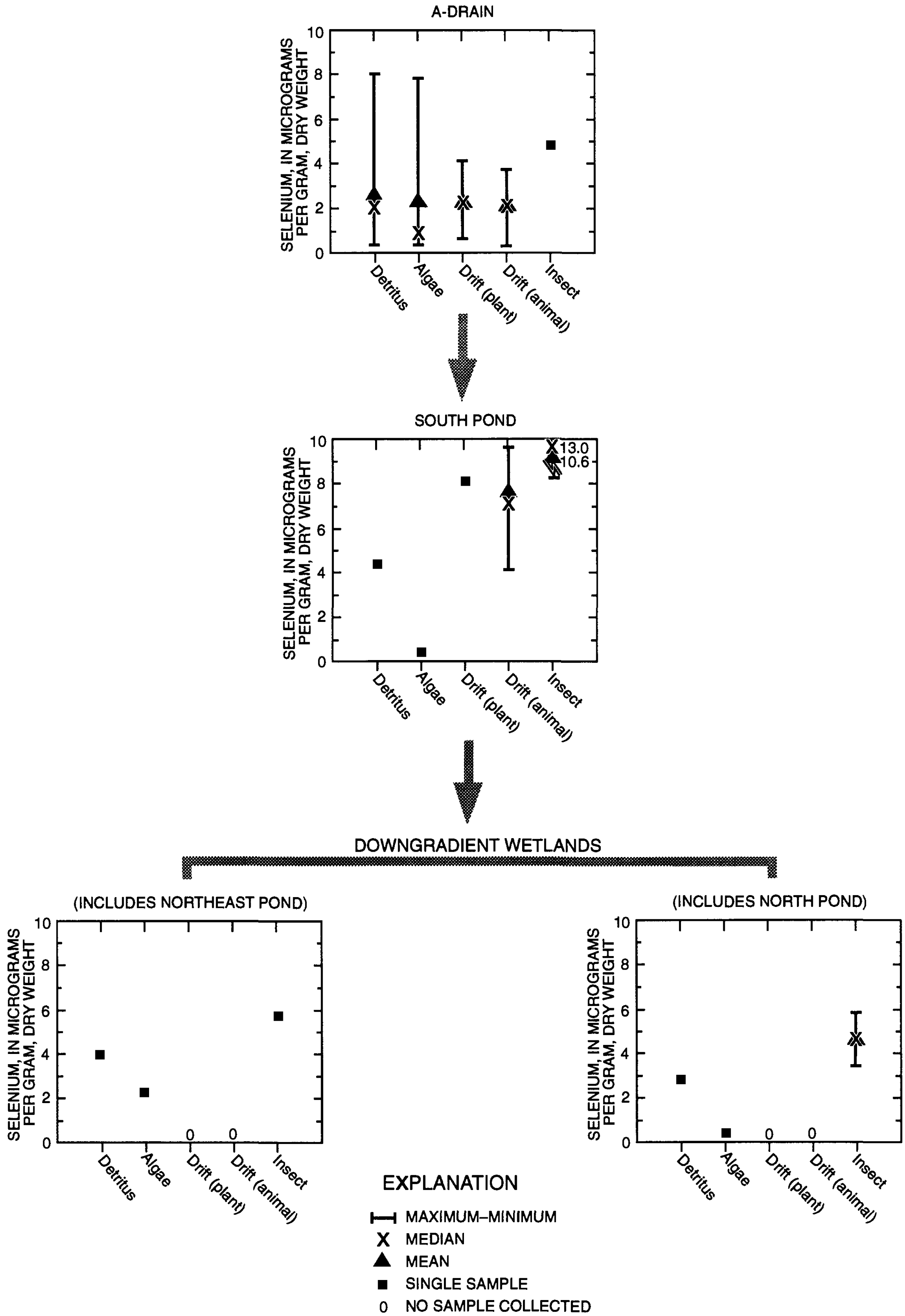

Figure 12. Generalized flow path and selenium concentrations in composite samples from A-Drain, South Pond, and downgradient wetlands, Fernley Wildlife Management Area. Data from Hoffman and others (1990, table 19) and Rowe and others (1991, tables 20 and 21).

Water is lost through evapotranspiration from Lead Lake and from managed ponds or wetlands downgradient to the extent that dissolved solids are concentrated two to six times in each successive wetland (U.S. Fish and Wildlife Service, 1988, p. 51). This process is cumulative, and dissolved-solids concentrations in the last wetland frequently exceed concentrations in seawater. Data on organically bound selenium from this study and on dissolved selenium (Hoffman and others, 1990, p. 37) do not conform to the simple evaporative patterns predicted from these concentration processes. Dissolved selenium is not a conservative variable; it was least present in water in the downgradient wetlands where dissolved solids were the most concentrated. Presser and Ohlendorf (1987, p. 811) also found that selenium distribution in sequentially arranged ponds was inversely related to that which would be predicted through evaporative models. Therefore, evapotranspiration does not appear to be an important mechanism contributing to selenium concentration in surface water.

Inorganic sediment deposition also is not believed to be playing an important role in selenium pathways within Lead Lake. Organic pathways were probably more effective at removing selenium from water than inorganic processes in the Grasslands Water District (Presser and Ohlendorf, 1987, p. 811). Although Lead Lake has received selenium-bearing drift for 7 years from TJ Drain and for more than 40 years from Paiute Diversion Drain, selenium concentrations in the upper 2-3.5 in. of the bottom sediment in Lead Lake averaged only 0.65 µg/g (mg/kg: Hoffman and others, 1990, p. 113), near the median range of concentrations in various organisms and detritus in Lead Lake. These concentrations suggest that, in this system, selenium is not accumulating or immobilizing in inorganic sediment over the long term. Roots of aquatic plants could have an active role in mobilizing selenium out of inorganic sediment (Lemly and Smith, 1987, p. 4), but most of the rooted aquatic plant beds have perished from Lead Lake over the last 30 years.

Organically bound selenium concentrations recorded in biota from Lead Lake are similar to those of the imported organisms and detritus found in drains (fig. 11). This indicates that an equilibrium between import and export exists in Lead Lake, which has been continuously flooded for about 10 years. Even with significant evaporative concentration processes, selenium concentrations in organisms from wetlands downgradient from Lead Lake are lower than those within the lake. Selenium volatilization may be a component of such an equilibrium (Ohlendorf, 1989, p. 139). Frankenberger and Thompson-Eagle (1989, p. 2) have documented volatilization of selenium from saline evaporation-pond water. The bacteria and fungi that were acting on the available selenium to cause this process were particularly effective in protein-rich environments. Organic detritus is a protein source and may facilitate volatilization of selenium in the study areas.

The selenium hazard to fish and wildlife in the Lead Lake system is largely determined by both concentration and length of exposure. Habitat size and configuration are important physical variables that determine the extent of wildlife use and exposure. The TJ Drain system is about 17 mi long, contains about 20 surface acres of flowing water, and attracts small numbers of migratory birds, primarily ducks. Conversely, Lead Lake covers about 1,000 acres and supports thousands of waterfowl. Because of relatively limited use, direct exposure of waterfowl to selenium in the TJ Drain is of lesser concern.

Concentrations of selenium in all types of biological samples from Fernley WMA were generally greater than those from the Lead Lake system. The relative concentrations of selenium in various organisms and spatial relationships are shown in figure 12. The relative concentrations of selenium in A-Drain, South Pond, and downgradient wetlands resemble the pattern described for the Lead Lake system but, like the Grasslands Water District (Presser and Ohlendorf, 1987, p. 815), bioaccumulation was greatest in the initial wetland.

Concentrations of selenium in drift, algae, and adult brine flies in Hunter Drain in Stillwater WMA (fig. 13) are comparable to those in both Fernley WMA and TJ Drain.

Mercury released to the Carson River in the late 1800's by gold and silver milling practices has contaminated the river sediment downstream of the Comstock mining district near Virginia City, Nev. (Smith, 1943; Cooper and others, 1985). Contaminated sediment is present over a large part of the Carson Desert, terminus of the Carson River. Mercury was deposited in the area through flooding prior to the construction of Lahontan Dam in 1915, and remains biologically available within Indian Lakes to this day. However, it appears that mercury export through the D-line Canal, a ditch that feeds the Indian Lakes, was minimal. The median concentration of mercury in composite detritus samples from

Indian Lakes, in Stillwater WMA, was about 53 µg/g, dry weight. In contrast, the median mercury concentration in detritus from the D-line Canal downstream from Indian Lakes was only 0.13 µg/g, which is comparable to background sites and at a level about 400 times lower than that in Indian Lakes.

Mercury concentrations found in 89 detritus and 76 algae samples from drains within the area ranged from <0.04 to 38.6 µg/g, and <0.02 to 10.4, respectively. Most of these high concentrations were from drainage/wetland systems not previously studied in detail for selenium accumulation. The mechanism(s) through which mercury was sorbed onto or into detritus and algae was not determined. Although drift was not examined in these drains, mercury was found in algae and detritus from drift moving down the drains in the area. Many of the samples with high mercury concentrations are from sites in drains upgradient of Carson Lake. Juvenile migratory birds have been shown to bioaccumulate mercury in Carson Lake (Hoffman and others, 1990, p. 61). Adult shoveler ducks (*Anas clypeata*) feeding in Carson Lake have also been shown to bioaccumulate mercury. (See the section in this report, "Mercury and Selenium in Edible Tissue of Waterfowl.")

In the three drainage systems examined in detail (Paiute, D-Line, and TJ Drains), biological pathways—particularly detritus and algae—were associated with the transport of selenium from irrigated lands (source areas) through drains to managed wetlands. Mercury also accumulated in detritus and algae in some drains. Because detritus and algae are transported in drift in similar drains in this project, biological pathways are thought to be involved in the movement of mercury from source areas to managed wetlands.

Duration of Selenium Contamination

Paiute Drain, which discharges to Lead Lake, provides additional information on the possible duration of selenium contamination in agricultural drainages. The Paiute Drain system (fig. 8) was constructed between 1913 and 1950. Median concentrations of selenium in animal drift from Paiute Drain were approximately half those of nearby younger TJ Drain and slightly less than half those from Hunter Drain (figs. 11 and 13).

The release of high concentrations of selenium in the shallow ground water, if present, in the first 1-5 years following construction of new drains, followed by the long-term release of lower concentrations would be expected (Gilliom and others, 1989, p. 123). The water-quality history of Paiute Drain is unknown, but it is apparent that after more than 40 years, selenium continues to be released into the water, incorporated into biota, and transported to Lead Lake (fig. 11). Similarly, after about 40 years of irrigation drainage, soils near Hunter Drain continue to release selenium into the water, and bioaccumulation occurs in this drain (fig. 13).

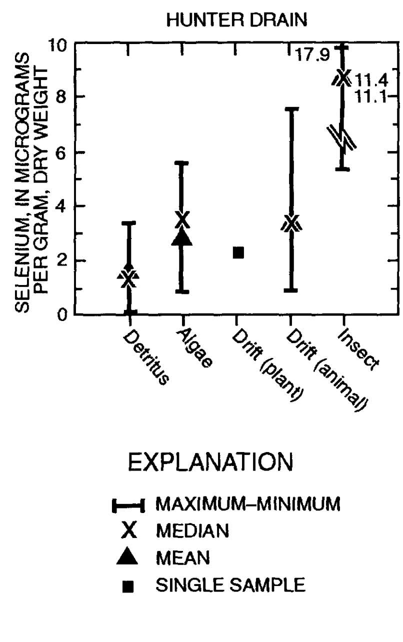

FIGURE 13. Selenium concentrations in composite samples from Hunter Drain in Stillwater Wildlife Management Area.

Contaminant Source Areas

Selenium and mercury are heterogenously distributed in irrigated soils within the Newlands Project area (R.R. Tidball, U.S. Geological Survey, oral commun., 1989). Here, source areas associated with biological pathways are irrigated land upgradient from or at sampling sites in drains that carried concentrations equal or exceeding 1.0 µg/g, dry weight, of selenium or mercury.

Figure 14 shows the spatial distribution of selenium in detritus throughout the study area Selenium concentrations in algae generally correlate with those in detritus. Areas having selenium concentrations ≥1.0 µg/g, dry weight, were defined as source areas or areas of high selenium availability. The 1.0 µg/g concentration was selected principally because of the capacity of selenium to biomagnify up the food chain. This concentration was the average for plants from TJ Drain. Four general source areas of high selenium concentration were identified: near the city of Fallon, north and east of S-Line Reservoir, Fallon Indian Reservation, and the Fernley agricultural area (fig. 9). Areas of high concentrations of arsenic and boron in detritus and algae coincided with the same areas of high selenium concentration (Rowe and others, 1991).

Areas having mercury concentrations ≥ 1.0 µg/g, dry weight, in detritus, were defined as source areas or areas of high mercury availability. Mercury concentrations greater than 1.0 µg/g were found in both detritus (fig. 15) and algae in an area near Carson Lake along the historical Carson River channel, south of Fallon. This fan-shaped area, generally northwest of Carson Lake, is the area which may have received sediment from the Carson River prior to 1900, before the construction of dams that diverted the flow of the river (see fig. 2). Other areas of high concentrations are along the Carson River, Stillwater Slough, and New River Drain.

The occurrence of selenium and mercury in detritus and algae associated with irrigation drainage is indicative of the bioavailability of those elements, and suggests an upgradient source. Furthermore, the magnitude of bioaccumulation at one site can be compared with another to indicate source areas of more or less contamination. Additional information on the annual load of organically bound selenium and mercury from the agricultural drains to receiving wetlands would be more definitive.

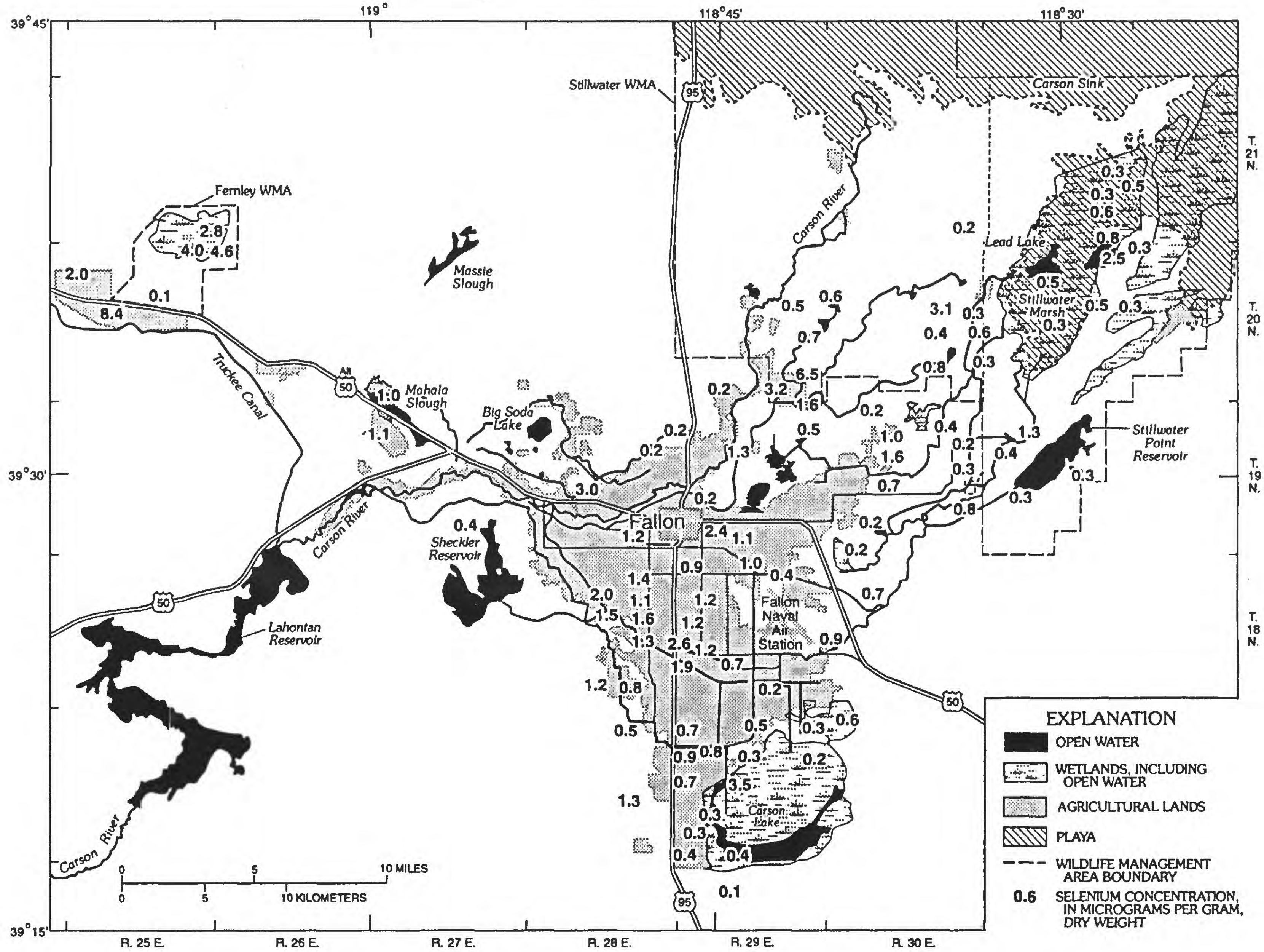

FIGURE 14. Concentrations of selenium in detritus samples from in and near Stillwater and Fernley Wildlife Management Areas. (Map modified from Seiler and Allander, in press.)

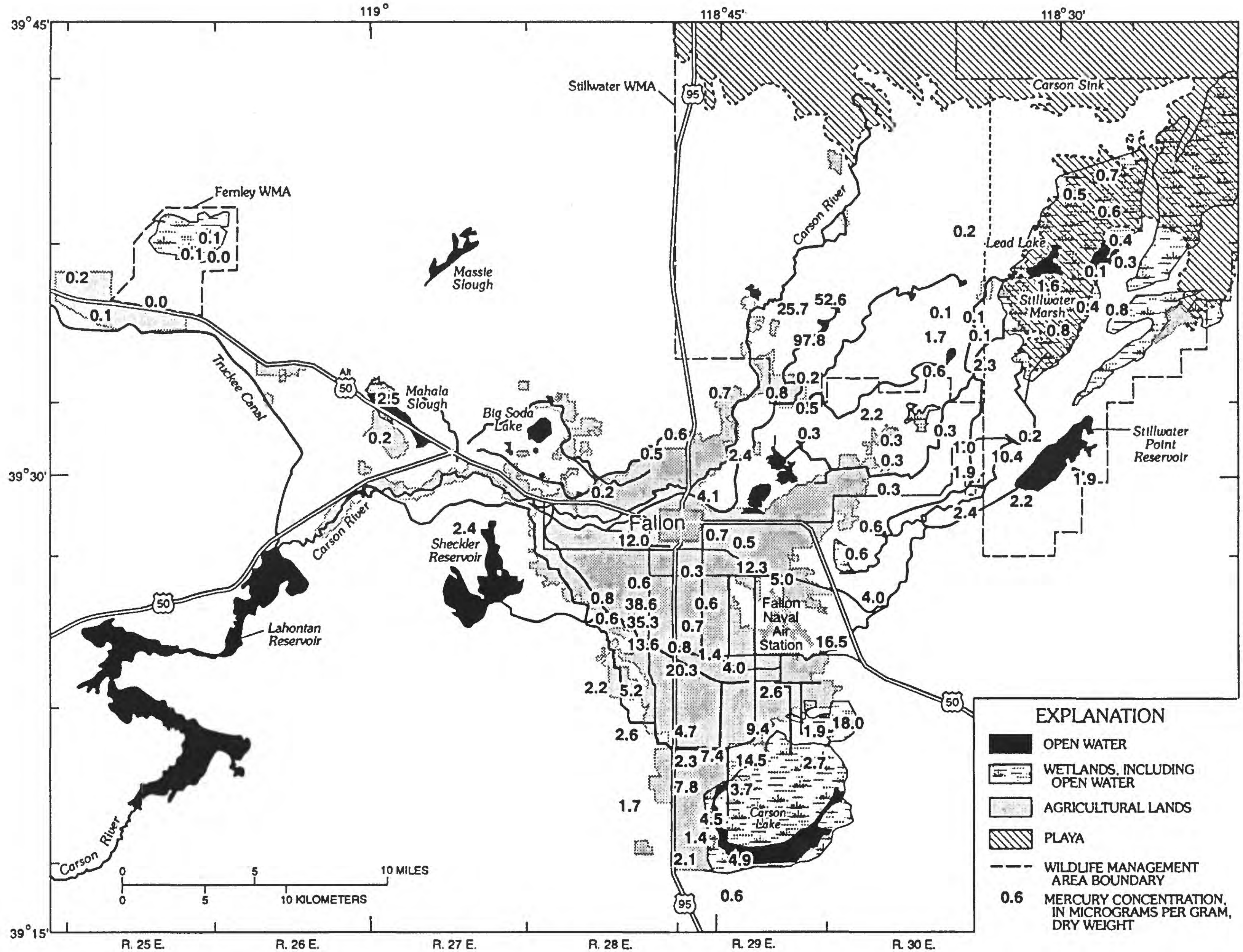

FIGURE 15. Concentrations of mercury in detritus samples from in and near Stillwater and Fernley Wildlife Management Areas and adjacent wetlands. (Map modified from Seiler and Allander, in press.)

(p. 55 follows)

EFFECTS OF BORON, MERCURY, AND SELENIUM ON WATERFOWL PRODUCTION

Waterfowl are typically most sensitive to environmental stress during their reproductive phases (egg formation, incubation, and juvenile growth) and are more vulnerable to the effects of trace elements during that time. Trace-element toxicity is a possible contributing factor to the steady decline of waterfowl production in wetlands that are maintained by drainage from the Newlands Irrigation Project. Livers from juvenile waterfowl and shorebirds collected from these wetlands in 1986-87 contained concentrations of boron, mercury, and selenium that have been associated with various harmful effects (Hoffman and others 1990, p. 53, 60, 67). The available literature concerning the effects of trace-element concentrations in eggs and juvenile waterfowl is limited, but some information is available about the effect levels of boron, mercury, and selenium. Concentrations of 20 trace elements were determined in this study in 1988 and presented by Rowe and others (1991, table 20). Of those elements, this section will consider only boron, mercury, and selenium. Evaluations of these three elements in eggs and juvenile duck livers and of hatch success, teratogenesis, nest success, and duckling production were made to determine the extent of the effects of these trace- elements on waterfowl reproduction.

APPROACH

Six separate wetlands were included in the waterfowl production study: Stillwater, Fernley, and Humboldt Wildlife Management Areas (WMAs); Carson Lake; and Massie and Mahala Sloughs (fig. 1). All of these areas receive irrigation drainage, ground water, or both, from U.S. Bureau of Reclamation Projects. Humboldt WMA is maintained primarily by irrigation return flow from the Humboldt Irrigation Project. The other five study areas receive irrigation return flow from the Newlands Irrigation Project (Hoffman and others, 1990).

Background sites were selected in Carson Valley, outside the study area, and at S-Line Reservoir, near the study area. The wetlands in Carson Valley are about 1,000 ft higher than the valley floors of the study area, thus presenting a history of soil development unaffected by ancient Lake Lahontan. Although S-Line Reservoir is located within the Fallon agricultural area, it is maintained primarily with Carson River water taken from Coleman Diversion Reservoir which contains only small amounts of irrigation return water.

This study was made in 1988 during the second year of a drought. Both irrigation drainwater and operational releases in the study area were greatly reduced because of the tight management of irrigation water; agricultural diversions were reduced to 70 percent of normal in response to the drought. Thousands of wetland acres dried up, reducing nesting and feeding habitat. Waterfowl congregated on the remaining wetlands, where reduced vegetative cover exposed nests to increased predation. Dissolved solids, including trace elements, concentrated in the drainwater and remaining ponds as evaporation reduced the water volume.

The number of samples collected in this study was low, primarily because nests that were not destroyed by predators were extremely difficult to locate in the available habitat. Nest predators were an ongoing problem, commonly destroying previously located nests between study visits.

Nests of six species of ducks—cinnamon teals (*Anas cyanoptera*), gadwalls (*Anas strepera*), mallards (*Anas platyrhynchos*), pintails (*Anas acuta*), redhead ducks, and ruddy ducks (*Aythya americana* and *Oxyura jamaicensis*)—were surveyed, as were nests of American coots (*Fulica americana*).

METHODS

Surveys to locate as many duck and coot nests as possible were conducted, on foot, in the various nesting habitats from early May through June. Peak nesting periods in this area typically range from April 10 to June 20 for ducks and from May 1 to June 15 for coots. All study sites had suitable nesting habitat for the various waterfowl common to the area. Redhead and ruddy ducks and American coots build nests in and over water in bulrush (*Scirpus sp.*) and cattails (*Typha sp.*), and other duck species use a variety of upland and marsh vegetation.

After the nests were located and identified by species, one egg was taken from each nest for trace-element analysis. Two additional eggs were collected from duck nests containing seven or more eggs for artificial incubation under controlled conditions to determine hatch success. Nests with six or fewer eggs were revisited and, if the clutch size had increased to seven, the additional two eggs were collected at that time. Coot eggs were not collected for artificial incubation because the incubator was adjusted for duck eggs and coots were of secondary interest. All eggs were marked for identification and floated in water to determine incubation stage and expected hatch dates (Westerkov, 1950). Eggs collected for trace-element analysis were immediately refrigerated and those for incubation were placed in a Koolatron (a temperature-controlled, padded container) for transportation to the incubator.

Eggs for trace-element analysis were volumetrically measured by water displacement. The eggs were then opened, using a scalpel cleansed with acetone followed by a distilled- or deionized-water rinse. The circumference of the egg was scribed with the scalpel and the contents dropped directly into a nitric-acid-washed, pre-weighed, 2-oz glass jar. The degree of embryonic development was recorded, and the samples were weighed, labeled, and frozen for shipment. All egg samples were analyzed for trace-elements by the U.S. Fish and Wildlife Service, Patuxent Analytical Control Facility, Laurel, Md., or their contract laboratories. The resulting data had appropriate quality-assurance documentation attached. All trace elements were analyzed by inductively coupled plasma emission spectroscopy, except for mercury, which was analyzed by the cold-vapor technique, and selenium, which was analyzed by hydride generation (U.S. Fish and Wildlife Service, 1985).

The incubator (a Petersime Model No. 4) was checked twice daily to monitor temperature and humidity and to remove any newly hatched ducklings. Eggs that remained unhatched approximately 10 days after expected hatch dates, and eggs that pipped but did not hatch, were removed and refrigerated for examination. Embryos and ducklings were examined for gross abnormalities of the eyes, beak, wings, and feet, and were then frozen in individual plastic bags. Mallard eggs of known age from game-farm birds maintained on a contaminant-free diet were used as incubation controls.

Coot nests were rechecked prior to expected hatch date and a second egg was collected from those nests still containing eggs. Embryos from these eggs were examined for deformities and then frozen.

To determine if juvenile birds accumulated trace elements after hatching, livers of juvenile ducks, coots, and black-necked stilts (*Himantopus mexicanus*) from both background and study-area wetlands were analyzed. Sixty preflight ducklings, 45 juvenile coots, and 12 juvenile stilts were collected from the study areas, and 5 ducklings and 6 coots were collected from the background areas. The birds were frozen and later partially thawed for dissection. The liver from each bird was removed using a scalpel rinsed with acetone followed by a distilled- or deionized-water rinse. The liver was placed in a nitric-acid washed, preweighed, 2-oz glass jar, then weighed, labeled, and frozen for shipment. Juvenile stilt livers were so small that two were combined to make a minimum sample weight; therefore, each data point for liver (figs. 16, 17) represents two birds.

Nest success is defined as the probability of production of one or more live juveniles from a nesting attempt. The nest-success rate was calculated by dividing the number of successful nests by the total number of nests. To determine nest success, each duck nest was checked at 7-10 day intervals for evidence of successful hatching. A feathered-egg membrane pulled away from the shell was used as an indicator of successful hatching. Coot nests were rechecked at least once, either at hatching time or just after.

Duckling production was estimated by conducting brood surveys in each study area from the fourth week of June through the third week of July—the peak hatching period Survey routes were predetermined to include areas of high brood use, particularly shorelines and clumps of vegetation, and to ensure adequate visibility by the investigator. Surveys started about 6:00 a.m., during the most active feeding time. Most routes were walked or driven, using binoculars or a spotting scope as necessary. In areas inaccessible by land, an airboat was used. Data on duck species, duckling numbers, and age classes at each site were recorded.

Hatch Success and Teratogenesis

Duck eggs for incubation and subsequent examination were collected from 41 nests; two eggs per nest were collected where possible. A total of 81 eggs were incubated—69 from study-area sites and 12 from background sites. Eggs from the background sites had a hatch-success rate of 92 percent. Of the 69 eggs from the study sites, 62 hatched—a success rate of 90 percent. This rate for artificially incubated duck eggs is in the range expected for eggs from healthy populations (Charles J. Henny, U.S. Fish and Wildlife Service, oral commun., 1990). Hatch success is summarized in table 16 by species and area.

The eight eggs that failed to hatch—seven from the study area and one from the background site—were examined for deformities. Five contained embryos, all well developed with no gross deformities (Charles J. Henny, U.S. Fish and Wildlife Service, oral commun., 1990). The three eggs that failed to develop may have been infertile. The 62 ducklings were also examined and no gross external deformities were observed. Thirty-one coot eggs from separate nests were collected just prior to expected hatch. Of these eggs, 24 had well-developed embryos and all 31 appeared to be normal. Based on these data, levels of trace elements in the eggs probably were below effect levels for teratogenesis and mortality.

Trace Elements in Eggs

Eisler (1990, 1987, and 1985) has summarized the available literature on the effects of boron, mercury, and selenium, respectively, on wildlife, including specific references for duck eggs (table 18). One of the common effects that each of these trace elements has on embryonic development is reduced hatch weight.

Concentrations of trace elements were determined for 62 duck eggs and 68 coot eggs. Five of the duck eggs were from the background site in Carson Valley and were well below the effect level for boron, mercury, and selenium. These data are reported by Rowe and others (1991, table 20) and are summarized in table 17 in this report.

Table 16. Hatch success of artificially incubated waterfowl eggs collected in the study area, 1988

[In each two-line data group, the top number (in parentheses) is total incubated eggs; bottom number is percentage hatched; --, no data; WMA, Wildlife Management Area]

Location	Cinnamon teal	Gadwall	Mallard	Pintail	Redhead	Ruddy	Total, all species
Study Sites							
Stillwater WMA	(6) 100	(2) 100	(4) 75	(4) 100	(2) 100	(2) 100	(20) 95
Fernley WMA	(6) 100	--	--	--	(6) 67	--	(12) 83
Humboldt WMA	(2) 100	(2) 100	(3) 100	--	(8) 88	--	(15) 93
Mahala Slough	(10) 80	(2) 100	(2) 100	--	--	(4) 75	(18) 89
Massie Slough	(2) 100	--	--	--	(2) 100	--	(4) 100
TOTAL	(26) 92	(6) 100	(9) 89	(4) 100	(18) 83	(6) 83	(69) 90
Background Site							
Carson Valley	--	--	(12) 92	--	--	--	(12) 92

The primary effects of high levels of boron are on growth, behavior, and brain biochemistry (Eisler, 1990, p. 19). Mallard ducklings from eggs with a boron concentration of 13 µg/g, dry weight, showed reduced hatch weights (Smith and Anders, 1989, p. 945). Eggs with boron concentrations of 49 µg/g, dry weight, showed significantly reduced hatch rates and juveniles from those eggs had higher mortality rates (Smith and Anders, 1989, p. 945). These effect levels came from feeding studies and are the arithmetic means resulting from experimental concentrations in feed, so no data on intermediate concentrations are available.

The boron concentrations found in eggs in this study (maximum, 19.4 µg/g, dry weight) were all well below the level known to adversely affect hatch success (49 µg/g, dry weight). This correlates with the incubator hatch rate of 90 percent observed in this study. Three redhead duck eggs (5 percent), all collected in Mahala Slough, had boron concentrations above 13.0 µg/g, dry weight, the level associated with reduced hatch weight. Overall, coot eggs had higher boron concentrations than duck eggs. Ten percent of the coot eggs, primarily those from Fernley WMA, had boron concentrations above the effect level for reduced hatch weight.

Table 17. Summary of data on concentrations of boron, mercury, and selenium, including minimums, maximums, and means for waterfowl eggs collected in the study area

[Abbreviations: µg/g, micrograms per gram; C. teal, cinnamon teal; WMA Wildlife Management Area.]

Location	Species	Number of samples	Trace-element concentration (µg/g, dry weight)								
			Boron			Mercury			Selenium		
			Minimum	Maximum	Mean	Minimum	Maximum	Mean	Minimum	Maximum	Mean
Study Sites											
Stillwater WMA	C. teal	3	3.2	4.8	4.1	1.6	6.2	4.5	2.0	2.3	2.2
	Gadwall	1	2.0	2.0	2.0	0.5	0.5	0.5	1.8	1.8	1.8
	Mallard	2	1.7	2.2	2.0	1.7	3.7	2.7	2.1	2.1	2.1
	Pintail	2	2.3	3.7	3.0	0.4	0.5	0.5	2.5	2.9	2.7
	Redhead	1	5.7	5.7	5.7	1.7	1.7	1.7	1.8	1.8	1.8
	Ruddy	2	1.1	1.2	1.2	0.2	0.5	0.4	2.1	2.9	2.5
Fernley WMA	Coot	25	5.5	15.7	9.3	0.1	0.4	0.1	4.4	12.2	8.7
	C. teal	2	1.7	4.8	3.3	0.2	0.7	0.5	7.6	10.1	8.8
	Mallard	1	3.1	3.1	3.1	0.2	0.2	0.2	8.9	8.9	8.9
	Redhead	3	3.2	5.4	4.2	<0.1	0.1	0.3	8.8	10.9	9.9
Humboldt WMA	Coot	27	4.4	14.3	7.7	0.1	1.36	0.2	1.9	4.48	2.9
	C. teal	2	2.8	5.2	4.0	0.4	0.5	0.5	2.8	3.7	3.2
	Gadwall	1	3.9	3.9	3.9	0.2	0.2	0.2	3.1	3.1	3.1
	Mallard	1	10.2	10.2	10.2	0.5	0.5	0.5	3.0	3.0	3.0
	Redhead	6	3.1	9.6	9.6	0.1	1.74	0.5	3.0	3.7	3.2
Mahala Slough	C. teal	9	1.5	7.6	4.1	0.2	1.1	0.6	2.0	7.4	4.4
	Gadwall	1	7.6	7.6	7.6	0.3	0.3	0.3	4.6	4.6	4.6
	Mallard	3	<0.8	0.9	0.6	0.3	2.1	1.1	1.3	8.4	4.0
	Redhead	7	4.2	19.4	11.7	0.1	1.2	0.6	1.2	8.5	3.7
	Ruddy	7	<0.8	3.1	2.1	0.1	2.7	0.6	1.2	5.7	3.3
Massie Slough	C. teal	1	1.7	1.7	1.7	0.1	0.1	0.1	8.0	8.0	8.0
	Redhead	1	1.8	1.8	1.8	0.4	0.4	0.4	3.6	3.6	3.6
	Ruddy	1	2.1	2.1	2.1	0.1	0.1	0.1	7.4	7.4	7.4
Background Site											
Carson Valley	Mallard	5	<0.8	1.9	0.7	0.2	0.6	0.3	0.7	2.3	1.4

Table 18. Effect levels and characteristics of boron, mercury, and selenium concentrations in waterfowl eggs and juvenile waterfowl livers

[µg/g, micrograms per gram]

Constituent	Eggs		Liver tissue	
	Effect level (µg/g, dry weight)	Characteristic sign or result	Effect level (µg/g, dry weight)	Characteristic sign or result
Boron[1]	13 49	Reduced hatch weight Reduced hatch rate and juvenile survival	17	Reduced reproduction and duckling growth
Mercury[2]	3.1	Reduced hatch rate and juvenile survival	4.3	Reduced reproduction and survival rates
Selenium[3]	15	Teratogenesis and embryo mortality	9	Reduced reproduction and juvenile survival

[1] Smith and Anders, 1989.
[2] Heinz, 1979.
[3] Lemly and Smith, 1987.

Mercury concentrations of 3.1 µg/g, dry weight, in black duck (*Anas rubripes*) eggs are associated with significantly reduced hatch rate and duckling survival (Heinz, 1979, p. 398). Mercury residues found in duck and coot eggs in this study were low except in those collected in Stillwater WMA. Three (27 percent) of the 11 duck eggs from Stillwater WMA had mercury concentrations above the effect level. The nest siblings of these eggs—cinnamon teal and pintail—hatched in the incubators.

All selenium concentrations found in duck and coot eggs were below 15 µg/g, dry weight. The level at which teratogenesis or embryo mortality (Lemly and Smith, 1987, p. 9), or reproductive problems in the laying hen (Heinz and others, 1989, p. 427) can be expected is 15-18 µg/g, dry weight.

The concentrations of potentially harmful trace elements in duck and coot eggs in all areas were low, with the exception of mercury in those from Stillwater WMA and, with that exception, probably are not a factor in waterfowl production. The adults of these species normally do not overwinter in these wetlands; they arrive shortly before nesting and apparently are not sufficiently exposed to the trace elements to accumulate enough to deposit significant amounts in their eggs.

Trace Elements in Juvenile Duck Livers

Eisler (1990, 1987, and 1985) summarized the available literature on the effects and concentrations of boron, mercury, and selenium in livers of juvenile waterfowl (table 18).

It was assumed that juvenile waterfowl collected preflight had been feeding in the vicinity and that the trace-element concentrations in their tissues reflected existing conditions in the wetlands. Juvenile ducks, coots, and black-necked stilts were taken from study areas where eggs had been collected, and livers were analyzed for concentrations of trace elements. Data were obtained for 65 preflight ducklings, 52 juvenile coots, and 12 juvenile stilts. Complete data are presented by Rowe and others (1991, table 20) and are summarized in this report (table 19).

In boron feeding studies, mallard ducklings with liver concentrations of 17 µg/g, dry weight, showed reduced weight gain (Smith and Anders, 1989, p. 945). In this study, boron concentrations in black-necked stilt livers (6 composite samples) were below 4 µg/g, dry weight. Concentrations of boron in duck livers also were below the effect level, varying widely throughout the study area from 1.1 to 15.1 µg/g. Coot livers showed higher boron concentrations than duck livers, as high as 34.5 µg/g. Concentrations of boron were at or above effect level in 10 percent of the coot livers. The highest boron concentrations were from Fernley WMA, where three of the seven coots collected had concentrations above effect level, and reduced growth rates could be expected. Boron levels in juvenile birds were not high enough to affect waterfowl reproduction

Levels of boron concentration varied; in some instances concentrations were higher in eggs than in juvenile livers from the same area. These data suggest that some adult birds may have acquired boron elsewhere in the flyway prior to their arrival and egg laying in the study areas.

Table 19. Summary of data on concentrations of boron, mercury, and selenium, including minimums, maximums, and means, for juvenile waterfowl livers collected in the study

[Abbreviations: µg/g, micrograms per gram; C. teal, cinnamon teal; WMA, Wildlife Management Area.]

Location	Species	Number of Samples	Trace-element concentration (µg/g, dry weight)								
			Boron			Mercury			Selenium		
			Minimum	Maximum	Mean	Minimum	Maximum	Mean	Minimum	Maximum	Mean
Study Sites											
Stillwater WMA	Coot	10	5.8	22.1	11.1	2.0	5.7	4.0	3.4	5.9	4.4
	C. teal	5	<2.0	4.4	3.2	1.4	3.5	2.2	4.0	6.8	5.6
	Mallard	2	5.1	9.8	7.5	2.7	3.0	5.6	7.4	9.0	8.2
	Pintail	1	5.9	5.9	5.9	1.8	1.8	1.8	6.6	6.6	6.6
	Redhead	2	5.0	6.0	5.5	2.4	6.4	4.4	6.7	13.9	10.3
	Ruddy	1	1.8	1.8	1.8	2.1	2.1	2.1	6.4	6.4	6.4
Fernley WMA	Coot	7	7.5	34.5	16.8	0.3	0.5	0.4	26.4	36.0	30.9
	C. teal	4	2.4	12.1	8.1	<0.1	0.1	0.1	26.4	35.3	30.3
	Stilt	3	2.0	3.5	2.5	0.4	1.0	0.7	17.0	35.3	28.4
Humboldt WMA	Coot	12	<2.0	8.0	4.5	0.2	3.2	0.7	7.8	13.0	10.1
	C. teal	6	1.8	5.1	3.2	0.4	1.6	1.0	11.9	17.5	15.1
	Gadwall	1	4.0	4.0	4.0	0.8	0.8	0.8	16.0	16.0	16.0
	Mallard	7	2.7	10.0	5.9	0.3	0.7	0.5	7.2	23.0	12.8
	Redhead	3	3.0	6.1	4.8	0.6	0.8	0.8	9.1	13.3	11.6
Carson Lake	Coot	10	1.6	6.8	4.9	2.0	8.8	5.3	2.6	6.3	4.4
	C. teal	1	7.9	7.9	7.9	5.6	5.6	5.6	8.7	8.7	8.7
	Mallard	4	<2.0	5.3	3.9	1.4	6.0	3.4	4.4	6.6	5.1
	Redhead	4	0.8	15.1	5.9	0.9	5.1	2.3	4.4	7.0	5.6
	Ruddy	4	2.1	3.9	3.3	<0.1	2.4	1.5	6.9	8.2	7.6
	Stilt	1	1.7	1.7	1.7	7.9	7.9	7.9	13.2	13.2	13.2
Mahala Slough	Coot	6	3.7	7.0	5.4	0.2	1.19	0.8	7.6	15.0	9.6
	Redhead	3	3.7	9.3	6.5	0.1	0.7	0.4	8.2	20.4	13.5
	Ruddy	6	<0.8	2.4	1.4	0.1	0.5	0.2	5.4	10.4	7.9
	Stilt	2	3.4	3.8	3.6	2.0	13.9	8.0	52.0	102.0	77.0
Massie Slough	Redhead	7	4.4	13.6	6.8	<0.1	0.5	0.3	17.5	43.5	30.7
Background Sites											
Carson Valley	Mallard	4	1.2	2.8	2.2	1.3	2.4	1.6	2.3	3.5	3.0
S-Line Reservoir	Coot	7	1.6	7.3	3.9	0.8	4.3	2.9	2.9	5.3	4.3
	C. teal	1	1.5	1.5	1.5	9.4	9.4	9.4	5.6	5.6	5.6

Data are not available for establishing an effect level for mercury concentration in juvenile waterfowl liver, but for adult mallard liver, an effect level of 4.3 µg/g, dry weight, for decreased reproductive success can be derived from existing data (Heinz, 1979, p. 396; Hoffman and others, 1990, p. 26). Stilt, duck, and coot livers from Fernley WMA and Humboldt WMA and Massie and Mahala Sloughs had mercury concentrations generally below 1 µg/g. Moderate concentrations of mercury in ducks, coots, and stilts were found in Carson Valley (mean 1.6 µg/g, dry weight) and in S-Line Reservoir (3.67 µg/g, dry weight). Mercury concentrations were above the effect level in 70 percent of the coots and 31 percent of the ducks from Carson Lake and 40 percent of the coots from Stillwater WMA. The highest mercury concentration found in this study, 13.9 µg/g, dry weight, was in a stilt sample (livers of two birds, combined) from Mahala Slough, an anomalous sample because no other samples from Mahala Slough showed high mercury concentrations, and Mahala Slough had not received direct Carson River water containing mining discharge. One of the birds in this sample probably was an adult that had moved into Mahala Slough from one of the nearby mercury-source areas.

The incidence of elevated mercury concentrations in birds was restricted to areas that had received mercury-contaminated sediment of the Carson River before construction of the Newlands Irrigation Project, including Carson Lake and Stillwater WMA. Mercury concentrations in bird livers from those areas are high enough that a negative effect on waterfowl production could be expected.

Data in the literature on the biological effects of selenium on waterfowl are more available. The effects are primarily on reproduction, but selenium toxicosis has been documented elsewhere since the 1930's. Selenium concentrations of 9 µg/g, dry weight, in livers of adult birds are known to be associated with decreased reproductive success and reduced juvenile survival (table 19; Lemly and Smith, 1987, p. 8). Selenium concentrations in livers establish 95 percent of equilibrium with dietary concentration in 7-8 days and return to background level 9-10 weeks after dietary intake stops (Heinz and others, 1990, p. 376). Selenium concentrations in livers of preflight juveniles, therefore, reflect the selenium in the food chain in the area.

Selenium concentrations in bird livers from Carson Valley and S-Line Reservoir (background sites), and Carson Lake were below the effect level for reduced reproduction (9.0 µ/g, dry weight). Twenty percent of the ducks from Stillwater WMA had selenium concentrations at or above effect level (fig. 16). In birds from Mahala Slough, concentrations of selenium above the effect level were found in 56 percent of the ducks, 33 percent of the coots, and both stilt samples. Concentrations in the two stilt samples (composite) were 52.0 and 102.0 µg/g (mean, 77 µg/g, dry weight), the highest found in this study and in the range where toxicosis and mortality have been documented elsewhere (Heinz and others, 1987, p. 429; 1988, p. 566). Livers from 83 percent of the ducks and 67 percent of the coots collected in Humboldt WMA had selenium concentrations above the effect level, as high as 23 µg/g, dry weight. High concentrations of selenium were also found in livers of cinnamon teal (mean, 30.0 µg/g, dry weight) and coots (mean, 30.9 µg/g, dry weight) from Fernley WMA, and in redhead ducks (mean, 30.7 µg/g, dry weight) from Massie Slough.

The two areas with the highest average concentrations of selenium in bird livers were Fernley WMA and Massie Slough, where every bird taken had concentrations between 17.0 and 43.5 µg/g (mean, 30.4 µg/g, dry weight).

Decreased survival of juvenile birds is anticipated in areas where liver concentrations are consistently above effect levels. Decreased juvenile survival and, thus, decreased waterfowl production, is anticipated in Fernley and Humboldt WMAs and Mahala and Massie Sloughs, and to a lesser extent in Stillwater WMA.

The concentrations of selenium residues found in juvenile livers were consistently higher than those found in eggs from the same areas, indicating juvenile uptake in all areas.

The combined effect of concentrations of two or more trace elements is not well understood. High boron concentrations were found with high selenium concentrations only in Fernley WMA. Selenium and boron have been considered to biochemically operate independently (Patuxent Wildlife Research Center, 1987, p. 28), but there is recent evidence that boron and selenium interact synergistically to produce more severe toxicological effects (David Hoffman, Patuxent Wildlife Research Center, written commun., 1990). With the exception of the anomalous stilt sample from Mahala Slough, high concentrations of mercury and selenium, in eggs or juvenile livers, were not found in the same areas.

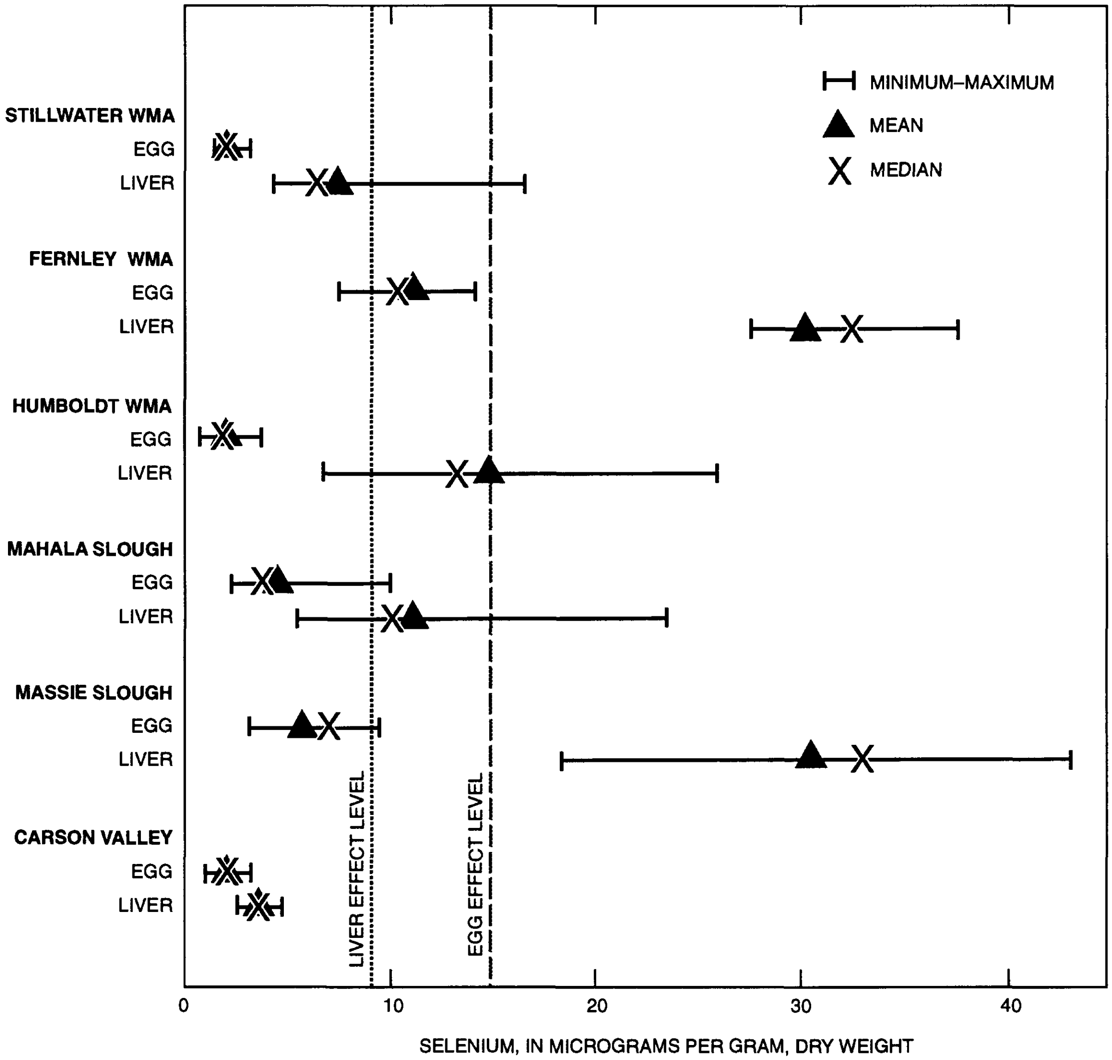

Figure 16. Concentrations of selenium in duck eggs and liver tissue of juvenile ducks collected in Stillwater, Fernley, and Humboldt Wildlife Management Areas, Mahala and Massie Sloughs, and at the background site. Effect levels for eggs and liver, 9 and 15 micrograms per gram, respectively, are described by Lemly and Smith (1987, table 2) and are summarized in table 18 of this report. Abbreviation: WMA, Wildlife Management Area.

Nest Success

Nest-success rate, by species, for each study area is summarized in table 20. The nest-success data from all study sites were combined, because of small sample sizes, and compared with data from nesting surveys conducted in Stillwater WMA in 1968-1970 (Napier, 1974), 1983 (Evans, 1983, p. 18-19), and 1987-1988 (Stillwater WMA, unpublished data); these comparisons are shown in table 21. The nest-success rate found in this study, 26 percent for the combined study sites, is comparable to the success rate of 25 percent determined for Stillwater WMA by the WMA staff. The nest-success rate at Stillwater has shown a general downward trend from 43-52 percent in 1968-70 to 25 percent in 1988.

No relation could be established between the nest-success rates in the various study sites and the trace-element concentrations in eggs or juvenile livers from those sites. The nest failure observed during this study appeared to be caused primarily by predation exacerbated by loss of habitat and the lack of vegetative cover in and near the remaining wetlands.

Table 20. Nest success of ducks in the study area, 1988

[In each two-line data group, the top number (in parentheses) is total nests examined; bottom number is percentage of nests hatching at least one young; --, no data; WMA, Wildlife Management Area.]

Location	Cinnamon teal	Gadwall	Mallard	Pintail	Redhead	Ruddy	Total
			Study Sites				
Stillwater WMA	(3) 100	(1) 0	(2) 50	(2) 100	(1) 0	(2) 0	(11) 55
Fernley WMA	2) 0	--	(1) 0	--	(3) 0	--	(6) 0
Humboldt WMA	(2) 0	(1) 100	(1) 100	--	(6) 50	--	(10) 0
Mahala Slough	(9) 22	(1) 0	(3) 33	--	(1) 0	(5) 20	(19) 21
Massie Slough	(1) 100	--	--	--	(1) 100	(1) 0	(3) 67
TOTAL	(17) 35	(3) 33	(7) 43	(2) 100	(12) 33	(8) 13	(49) 26
			Background Site				
Carson Valley	--	--	(6) 83	--	--	--	(6) 83

Waterfowl Production

A survey of waterfowl breeding pairs, conducted annually in mid-May by the Nevada Department of Wildlife, found 6,810 breeding pairs of various species of ducks in the study area in 1988 (Nevada Department of Wildlife, unpublished data, 1988). The low number of duck nests (49) found in this study, and the difficulty experienced in finding even that number, suggests that most of the breeding pairs present in mid-May did not nest. Nesting habitat in the study area and in other traditional nesting areas is greatly reduced from that available in the recent past (U.S. Department of the Interior, 1988). This lack of habitat may be preventing many pairs from nesting.

Observed duckling production from all study areas except Stillwater WMA was 579 birds. Brood production in Stillwater WMA, estimated by the Stillwater staff, was about 1,800 ducklings (U.S. Fish and Wildlife Service, Fallon, Nev., unpublished data, 1988), for a total estimated production of about 2,400 waterfowl (table 22). The brood counts in Fernley WMA, Humboldt WMA, and Carson Lake were close to estimates made by the Stillwater WMA staff. Duckling production in 1988 was considerably lower than production experienced in previous years (U.S. Fish and Wildlife Service, Fallon, Nev., unpublished data, 1988).

Waterfowl production typically fluctuates, and is dependant on a variety of factors, including the availability of suitable wetland nesting habitat and predator populations. Decreased water flow to the wetlands, management choices about use of the remaining water, and elevated dissolved-solids concentrations—shown to cause vegetative losses (U.S. Fish and Wildlife Service, 1988, p. 74)—are all probable contributing factors to decreases in nesting habitat. The continuing decrease in waterfowl production observed in the study area in recent years is associated with decreased feeding and nesting habitat that results in waterfowl nesting in marginal areas, and to increased predation rates resulting from a concentration of predators foraging in reduced wetland areas.

Table 21. Nest-success rates from various other studies and from the present study

[In each two-line data group, the top number (in parentheses) is total nests examined; bottom number is percentage of nests hatching at least one young.]

Duck species	Other studies (Stillwater Wildlife Management Area)				Present study (all sites)
	1968-1970[1]	1983[2]	1987[3]	1988[3]	1988
Cinnamon Teal	(43-56) 49-56	(100) 28	(7) 29	(25) 32	(17) 35
Gadwall	(19-42) 16-43	(23) 13	(17) 6	(26) 8	(3) 33
Mallard	(1-7) 0-43	(7) 57	(5) 20	(15) 33	(7) 43
Pintail	(2-4) 50-80	(6) 17	(5) 0	(7) 29	(2) 100
Redhead	(4-7) 57-100	(11) 91	(7) 14	(3) 67	(12) 33
Ruddy	(1-3) 67-100	(5) 60	(2) 0	(1) 0	(8) 13
TOTAL	(87-118) 43-54	(152) 32	(43) 33	(77) 25	(49) 26

[1] Napier, 1974.
[2] Evans, 1983.
[3] Unpublished data from U.S. Fish and Wildlife Service, Fallon, Nev.

Table 22. Estimated waterfowl production in the study area, 1988

Site	Cinnamon teal	Gadwall	Mallard	Pintail	Redhead	Ruddy	Other	Total
Stillwater WMA[1]	300	310	66	173	150	690	82	1,771
Fernley WMA	31	0	11	0	0	0	0	42
Humboldt WMA	45	36	17	0	0	0	0	98
Mahala Slough	12	14	12	6	12	30	0	86
Massie Slough	50	26	50	8	50	5	0	189
Carson Lake	45	18	24	1	32	44	0	164
TOTAL	483	404	180	188	244	769	82	2,350

[1] Estimates from U.S. Fish and Wildlife Service, Fallon, Nev. (unpublished data). All other data are from this study.

MERCURY AND SELENIUM IN EDIBLE TISSUE OF WATERFOWL

The reconnaissance study during 1986-87 found indications that juvenile migratory birds, including waterfowl, in and near Stillwater WMA and Carson Lake were accumulating mercury and selenium in liver and muscle tissue and some of the concentrations exceeded established criteria for public-health warnings (Hoffman and others, 1990, p. 60-62, 66-70). Waterfowl taken from these areas are routinely consumed by hunters. Further sampling done in October 1987 and in 1989 for the detailed study found continued high concentrations of mercury and selenium in edible tissues of waterfowl that could affect public health. Accumulation of selenium and mercury between waterfowl species within wetland systems and between different wetlands supporting the same species varied. This study focused primarily on Stillwater WMA and Carson Lake, the largest public waterfowl-hunting areas associated with the Newlands Irrigation Project, but because waterfowl are also hunted at nearby Fernley WMA and at Massie and Mahala Sloughs, those areas were included in the present study (fig. 1).

APPROACH AND METHODS

Ducks of various ages harvested in mid-October 1989 at the beginning of waterfowl-hunting season, were considered to be representative of waterfowl consumed by humans. Most ducks evaluated in this study were contributed by hunters passing through USFWS check stations near Stillwater WMA and Carson Lake during the opening weekends of the waterfowl seasons; species included were shovelers (*Anas clypeata*), mallards (*Anas platyrhynchos*), green-winged teals (*Anas crecca*), canvasbacks (*Aythya valisineria*), and redhead ducks (*Aythya americana*). Shovelers, late summer-early fall migrants that rarely nest in the study area, were collected from Carson Lake during August 1989 soon after they arrived and again in mid-October 1989. The mercury and selenium concentrations of the August birds served as a baseline against which to establish the increase in concentration of these trace elements between August and the mid-October hunting season. Green-winged teals also were collected in October 1989 from Carson Lake.

Whole ducks were identified, tagged, stored on ice in the field, and frozen in the laboratory on the date of collection. The ducks were thawed and later dissected. To prevent cross contamination, rubber gloves were worn and stainless-steel instruments were rinsed in acetone, then distilled or deionized water. Tissue samples were weighed and refrozen in labeled, nitric-acid-rinsed 2-oz jars. Concentrations of mercury and selenium in muscle, liver, and skin were evaluated.

Tissue samples were analyzed by the U.S. Fish and Wildlife Service, Patuxent Analytical Control Facility, Laurel, Md., or its contract laboratories. The resulting data had appropriate quality-assurance documentation attached. Mercury was analyzed by cold-vapor techniques and selenium was analyzed by hydride generation. Associated procedures used are described by the U.S. Fish and Wildlife Service (1985). Data were reported by the laboratory in micrograms per gram, dry weight. Because the purpose of this section of the report is to compare concentrations found with established criteria or action levels for human consumption, all data have been converted to wet weight, by dividing by 3.6 (Lemly and Smith, 1987, p. 7). An action level is a concentration of a contaminant in animal tissue used for human food at which responsible agencies take action. It is derived from a hazard-risk assessment and includes a safety margin for the population deemed most likely to consume the food involved. Typically, with wildlife not involved in commerce, the action taken is posting of public health warnings. Analysis of variance was used to examine temporal relations of contaminant levels. A statistical significance of 0.1 was selected.

Action levels established by the U.S. Food and Drug Administration (FDA) and the State of California were used to evaluate the potential threat to human health. The U.S. FDA (1984, p. 1) action level for mercury in edible animal tissue is 1.0 µg/g, wet weight, and the State of California action level for selenium is 2.0 µg/g, wet weight (Fan and others, 1988, p. 544).

During the October 1987 sampling period, mallards, redheads, and shovelers were collected from both Carson Lake and Stillwater WMA. Canvasbacks were collected only from Stillwater WMA. The data were published by Rowe and others (1991). The action level for mercury concentrations was exceeded in almost half of the ducks sampled. Selenium concentrations exceeded the action level in less than 15 percent of the samples. Mercury and selenium concentrations were highest in liver, lower in muscle, and least in skin samples. Concentrations in skin never exceeded the action levels. Muscle is of greatest concern because it is the preferred tissue of most humans who consume ducks; liver and skin are less frequently eaten.

Mercury Accumulation in Waterfowl

Hoffman and others (1990, p. 60-62) found that mercury concentrations in liver and muscle tissue of juvenile mallards and liver tissue of coots (*Fulica americana*) and black-necked stilts (*Himantopus mexicanus*) collected in 1986 and 1987 from Carson Lake exceeded the action level. Juvenile birds, too young to migrate, were assumed to have acquired most of this mercury locally through diet. Henny and Herron (1989, p. 1043) documented accumulation of mercury in white-faced ibis (*Plegadis chihi*) which feed in fields near Carson Lake. Mercury concentrations in liver tissue of juvenile black ducks (*Anas rubripes*) were found to nearly double in 4 weeks when the ducks were fed a diet containing 3 µg/g mercury, and the rate of accumulation in liver was greater than in muscle (Finley and Stendell, 1978, p. 60).

Mercury concentrations in shoveler ducks collected in October 1987 from Carson Lake exceeded the action level (or public-health criterion of 1.0 µg/g, wet weight; 3.6 µg/g, dry weight) in every liver sample and in 90 percent of the muscle samples (fig. 17). Mercury concentrations in shoveler muscle and liver from the October 1987 data set were the basis for the Nevada State Health Officer's decision to post a public-health warning specific to shoveler ducks at Carson Lake in 1989. The mean concentrations of mercury in shoveler muscle and liver from Carson Lake were, respectively, about 6 and 18 times the action level of 1.0 µg/g, wet weight. At the request of the State Health Officer, shovelers were again analyzed by the Department of the Interior in 1989. The concentrations of mercury in muscle were lower, but still averaged three times the action level, and the public-health warning stayed in effect. Concentrations exceeding the action level for mercury were also found in some shovelers from Stillwater WMA (fig. 17), in some green-winged teal from Carson Lake, and in mallards from both locations (fig. 18).

The shoveler ducks collected from Carson Lake in mid-August 1989 for baseline data had a mean concentration of mercury in muscle tissue of 1.1 µg/g, wet weight (fig. 17), significantly lower ($p=<0.05$) than the 5.9 µg/g mercury level found in shoveler ducks collected in October 1987. A lesser, but still significant difference ($p=0.08$) was found between the shovelers collected in August 1989 and those collected in October 1989. The shovelers collected in October 1989 contained a mean of 2.8 µg/g, wet weight, mercury in muscle tissue.

The significant difference ($p=<0.05$) found between the 1987 and the 1989 mercury concentrations in shovelers from Carson Lake may be related to wetland availability. In 1987, both the Island Unit and Sprig Pond in Carson Lake contained water, but in 1989 only Sprig Pond was flooded. Composite sediment data gathered by Hoffman and others (1990, p. 113) indicated that mercury was twice as abundant in the Island Unit (18 mg/kg) as in Sprig Pond (9 mg/kg). The time of shoveler arrival and exposure (up to 8 weeks) was similar in both years.

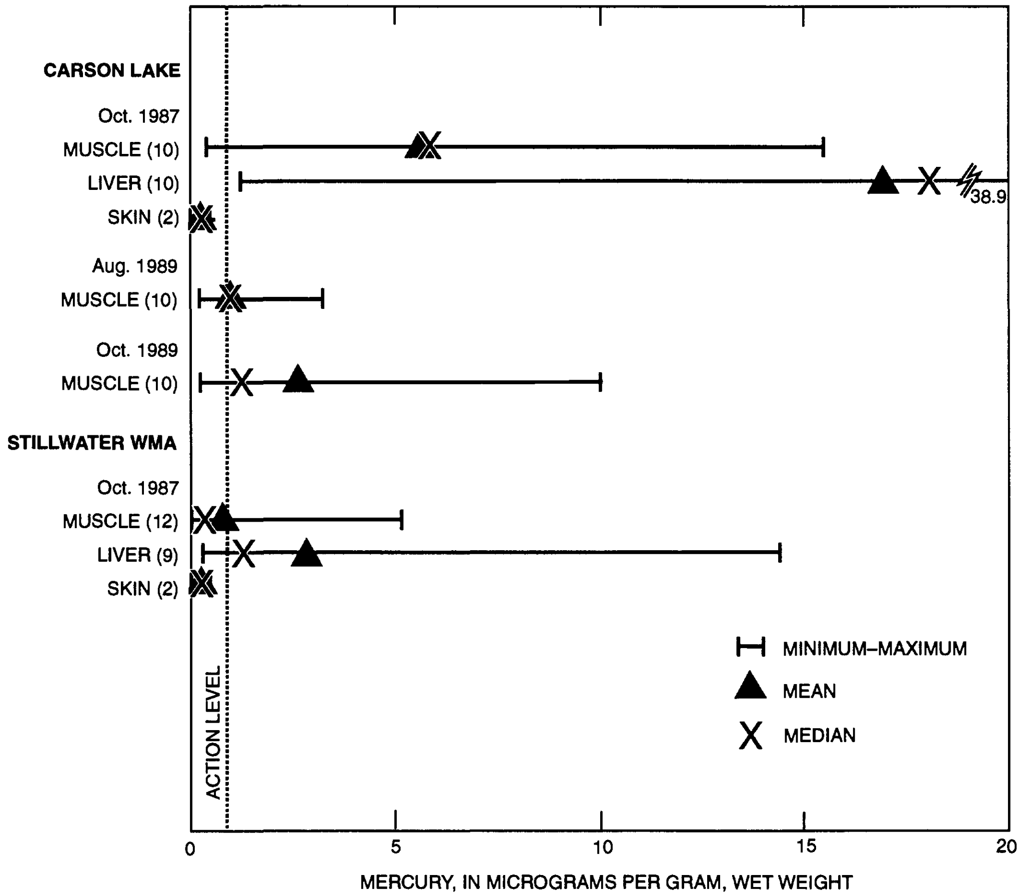

FIGURE 17. Concentrations of mercury in edible portions of shoveler ducks collected at Stillwater WMA and Carson Lake. Number of samples in parentheses. The action level is 1.0 microgram per gram, wet weight (U.S. Food and Drug Administration, 1984, p. 1).

Differences in mercury concentrations between duck species was apparent in October 1987, when the widest variety of species was collected (figs. 17 and 18). Shovelers from Carson Lake had the highest concentrations of mercury, with all liver samples and 90 percent of the muscle samples exceeding the action level. Mercury concentrations in mallards from Carson Lake exceeded the action level in 70 percent of the liver and 20 percent of the muscle samples. Mean and median mercury concentrations were below the action level in muscle tissue of green-winged teal, redheads, and canvasbacks (fig. 18).

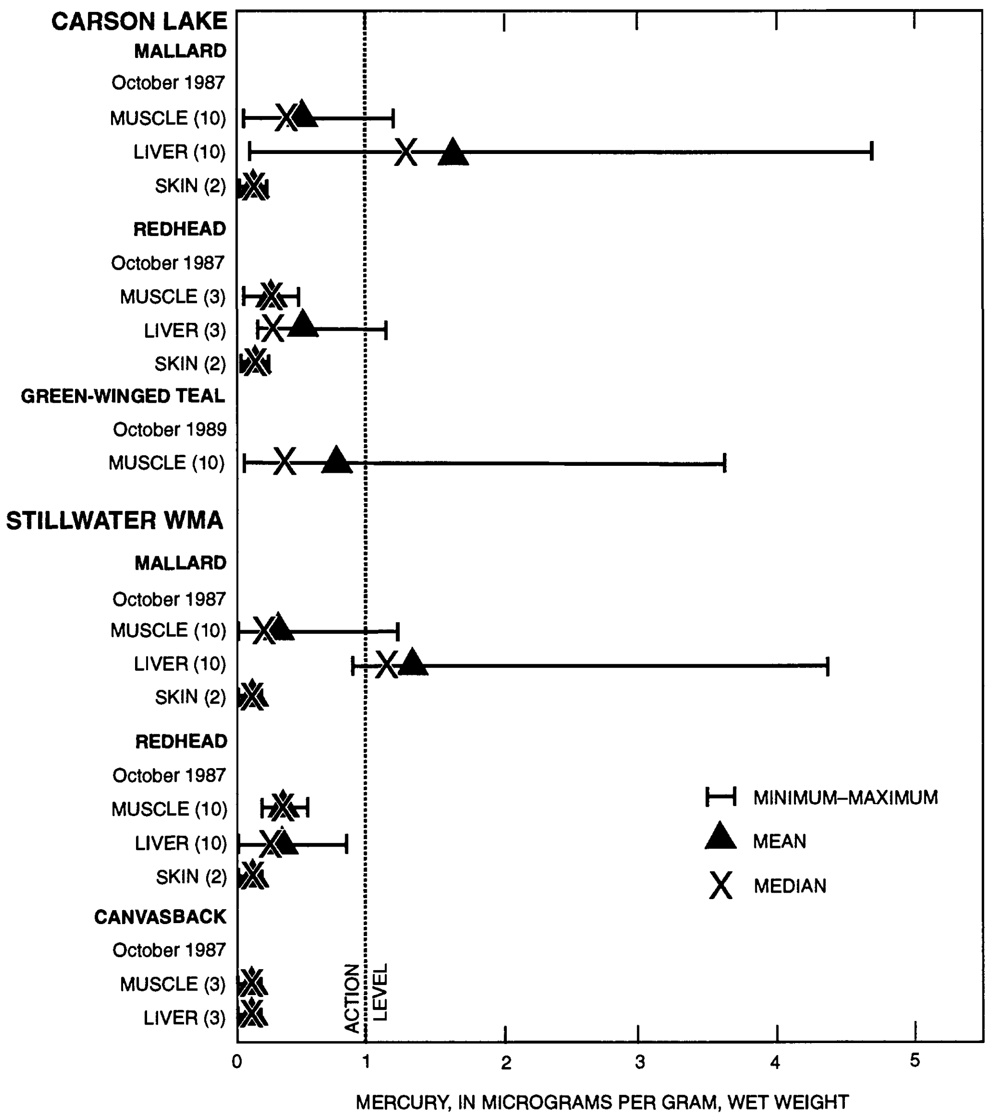

Figure 18. Concentrations of mercury in edible portions of various duck species collected at Stillwater WMA and Carson Lake during the opening week of waterfowl season, October 1987. Number of samples in parentheses. The action level is 1.0 microgram per gram, wet weight (U.S. Food and Drug Administration, 1984, p. 15).

Selenium Accumulation in Waterfowl

Although Hoffman and others (1990, p. 66-70) reported selenium concentrations much higher than the action level of 2.0 µg/g, wet weight, in liver tissue of various juvenile migratory birds from the study area, less than 15 percent (8 of 58) of livers from various waterfowl collected in October 1987 from Carson Lake and Stillwater WMA exceeded 2.0 µg/g. However, within this data set, 10 shoveler livers taken on October 17, 1987, contained a mean selenium concentration of 2.2 µg/g and ranged from 0.8 to 3.8 µg/g. Shovelers are fall migrants believed to have been in these wetlands up to 6 weeks prior to collection. None of the muscle samples from these birds contained selenium concentrations above 2.0 µg/g (Rowe and others, 1991, p. 118-151).

Fernley WMA could not be evaluated during the 1989 hunting season because it was dry by mid-October and, therefore, contained no ducks. However, during July 1988, juvenile cinnamon teal (*Anas cyanoptera*) and coots with mean selenium concentrations in livers of 8.4 and 8.6 µg/g, wet weight, respectively, were collected from Fernley WMA. Selenium in livers of juvenile redhead ducks from Massie and Mahala Sloughs averaged 8.5 µg/g and 3.7 µg/g, wet weight, respectively, as reported in the preceding section on waterfowl production. In a study of mallards, Heinz and others (1990, p. 374) found that after 81 days on a selenium-rich diet, concentrations of selenium were slightly higher in muscle than in liver tissues. This suggests that by October, at the start of hunting season, if the juvenile ducks had remained in Fernley WMA and Massie Slough they might have had selenium concentrations in muscle that were higher than the concentrations found in July (>8.0 µg/g), which was already more than four times the established human-health criteria.

Differing lengths of waterfowl residence in the wetlands may account for some of the variability in the data from this study. Other important factors determining intake of potentially toxic constituents are dietary preferences and the specific wetlands selected by birds.

(p. 71 follows)

OVERALL SUMMARY OF EFFECT OF IRRIGATION DRAINAGE ON BIOTA

Important findings of the five biologically related study elements addressing possible adverse effects of irrigation drainage on biota in and near Stillwater WMA are summarized here. The goal of the investigation was to (1) determine the effects of irrigation drainage on migratory waterfowl that frequent these wetlands and (2) provide information for resource-management decisions and subsequent remediation strategies. Major findings of the studies, in order of presentation, are:

- Historical wetlands in Carson Lake, Stillwater Marsh, and Carson Sink averaged about 150,000 acres. Under the Operating Criteria and Procedures mandates, fully implemented in 1992, only about 10 percent, or 15,000 wetland acres, are projected to remain in nearly permanent impoundments.
- Average dissolved-solids concentration in drainwater entering these wetlands has increased about seven-fold from the estimated historical 170 mg/L to a current average of 1,170 mg/L. This increase in concentration has occurred largely through evapotranspiration associated with irrigated agriculture. Although the annual dissolved-solids load has decreased in these now-isolated wetlands, the increased concentrations have adversely affected the various plants, invertebrates, fish, and wildlife that were once abundant in the historical wetlands.
- During acute-toxicity tests, organisms in control water survived wide fluctuations in specific conductance that ranged from 410 to 27,500 µS/cm (252 to 17,900 mg/L dissolved solids). Organisms in undiluted drainwater samples subjected to similar fluctuations in dissolved-solids concentrations did not survive. Surface water from TJ and Hunter Drains and ground water from a shallow well near TJ Drain were acutely toxic to all test organisms.
- Analysis of undiluted drainwater showed that four potentially toxic elements—arsenic, boron, lithium, and molybdenum—were representative of the overall levels of toxicity in the water tested. Strong, positive relations were found between the aggregate of arsenic, boron, lithium, and molybdenum and both daily and average dissolved-solids concentration. Thus, specific conductance may be a useful measure of surface-water quality for management of fish and invertebrate populations in Stillwater WMA.
- Within drains, both mercury and selenium are being bioaccumulated in plants and plant detritus and biomagnified in invertebrates by factors of up to 10,000 times the concentrations measured in associated drainwater.
- Mercury and selenium are being transported in living organisms and their detritus. Transport is from irrigated land, by way of irrigation drains, to large wetlands where most migratory birds, fish, and other wildlife are exposed to these elements.
- Source areas of mercury and selenium in the Newlands Irrigation Project area are areas generally upgradient from sampling sites in drains where concentrations exceeded concern levels of 1.0 µg/g, dry weight, in detritus.
- Although selenium continues to be released from some irrigated soils more than 40 years after initiation of irrigation, and is being carried by plants and invertebrates through the drains, no evidence was found to indicate a long-term build up of selenium in the sediment and biota of downgradient wetlands.

- Potential contaminant concentrations in waterfowl eggs from the study sites were generally below published effect-level criteria and would not be expected to affect bird production. Consistent with these data, no teratogenesis was observed in embryos or hatchlings. The hatch rate of waterfowl eggs was normal, 90 percent or more, at both study and background sites.

- Concentrations of boron, mercury, and selenium at adverse effect levels were found in juvenile migratory birds from several study sites. Concentrations of selenium as high as 30 µg/g were found in duck and coot livers from Fernley WMA and Massie Slough, and 77 µg/g in black-necked stilt livers from Mahala Slough. Decreased survival and, thus, production may be expected among birds containing selenium concentrations in this range.

- Nest success was poor throughout the study areas, averaging only 26 percent. Loss of feeding habitat and nesting cover caused by drought, increased dissolved-solids concentrations, and predation are the primary reasons for reduced nest success. Thus, waterfowl production is now much reduced compared to historical conditions.

- Shoveler ducks harvested by hunters from Carson Lake had accumulated mercury in muscles and livers, 5.9 and 17.8 times greater, respectively, on average, than the 1.0 µg/g, wet weight, action level for human consumption. In response to the elevated mercury concentrations, the State of Nevada posted human-health warnings at Carson Lake specific to shoveler ducks.

- Concentrations of selenium in juvenile-waterfowl livers from Fernley WMA and Massie Slough in July 1988 averaged more than 8.0 µg/g, wet weight, or more than four times the 2.0 µg/g, wet weight, criterion for human consumption. Because of drought, no birds were present in these areas in October 1989 for collection and evaluation; thus, the potential for human-health concerns in these areas could not be fully evaluated.

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SUPPLEMENTAL WATER-QUALITY DATA FROM TOXICITY STUDY

Table 23. Water-quality measurements for daily composite water samples from Paiute Diversion Drain, August 1988

[Concentrations in milligrams per liter except as indicated. All mercury concentrations were below analytical reporting limit. Abbreviations: µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25°C; NTU, Nephelometric turbidity units; ppt, parts per thousand.]

Date	Specific conductance (µS/cm)	Field pH	Onsite mobile lab pH	Turbidity (NTU)	Dissolved oxygen	Calcium	Magnesium
August 10	420	7.5	8.2	31	6.8	33	11
11	370	8.4	8.2	35	8.9	31	10
12	480	8.3	8.4	33	7.7	35	12
13	390	8.0	8.3	32	7.3	33	11
14	400	8.3	8.1	16	9.7	35	12
15	400	8.5	8.4	15	8.9	36	12
16	400	8.5	8.5	25	8.8	35	11
17	383	8.6	8.6	20	9.0	35	13
18	430	8.6	8.6	18	8.7	36	11

Date	Hardness	Sodium	Potassium	Alkalinity	Sulfate	Chloride	Silica
August 10	120	72	3.8	142	85	63	5.8
11	110	62	2.8	111	68	58	6.3
12	130	84	3.9	146	64	50	7.0
13	120	68	4.9	133	60	55	6.7
14	130	75	5.4	138	72	60	6.6
15	140	79	5.3	145	72	60	6.9
16	130	72	4.4	158	52	65	6.8
17	130	82	4.7	135	52	70	7.2
18	130	73	3.9	157	60	65	6.6

Date	Salinity (ppt)	Nitrate as N	Ammonia as N	Phosphorus	Arsenic	Barium	Boron
August 10	0.2			0.1	0.01	0.08	0.58
11	.2			<.1	.02	.08	.52
12	.3	<0.01	0.16	.1	.02	.08	.76
13	.2			.1	.02	.08	.58
14	.1	<.01	.06	.1	.02	.09	.60
15	.1			.1	.02	.08	.63
16	.1			.1	.02	.07	.60
17	.1	<.01	.04	.2	.02	.07	.55
18	.2			<.1	.02	.08	.61

Date	Lithium	Molybdenum	Selenium (µg/L)	Strontium	Vanadium	Zinc
August 10	0.06	0.02	<0.3	0.37	0.01	0.07
11	.05	<.02	.3	.35	.01	.03
12	.06	.02	.3	.40	.01	.03
13	.06	<.02	.3	.37	.01	.05
14	.06	.02	.3	.40	.01	.04
15	.06	.02	.3	.41	.01	.05
16	.06	<.02	.3	.38	.01	.03
17	.06	<.02	.3	.41	.01	.02
18	.06	.02	.3	.40	.01	.03

Table 24. Water-quality measurements for daily composite water samples from TJ Drain, August 1988

[Concentrations in milligrams per liter except as indicated. All mercury concentrations were below analytical reporting limit. Abbreviations: µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25°C; NTU, Nephelometric turbidity units; ppt, parts per thousand.]

Date	Specific conductance (µS/cm)	Field pH	Onsite mobile lab pH	Turbidity (NTU)	Dissolved oxygen	Calcium	Magnesium
August 10	8,100	8.5	8.5	2	7.4	180	200
11	12,000	8.5	9.0	3	8.4	260	320
12	11,800	8.6	8.5	2	8.7	240	300
13	14,900	8.5	8.3	3	8.7	310	410
14	11,000	8.6	8.4	2	9.2	230	290
15	6,100	8.4	8.1	4	8.3	140	160
16	7,200	8.4	8.3	4	8.9	160	180
17	13,700	8.5	8.4	3	8.7	290	360
18	14,300	8.6	8.4	8	10.9	210	250

Date	Hardness	Sodium	Potassium	Alkalinity	Sulfate	Chloride	Silica
August 10	1,300	2,000	29	232	1,400	2,700	2.1
11	1,900	3,500	42	289	2,900	4,800	.9
12	2,000	3,300	40	263	2,900	4,900	2.0
13	2,500	4,700	57	319	3,600	6,200	.6
14	1,800	3,400	43	276	1,600	4,700	.1
15	1,100	1,900	29	224	880	3,800	3.7
16	1,300	1,900	29	217	1,500	5,800	2.9
17	1,900	4,000	50	292	1,600	4,900	.8
18	1,700	2,900	39	244	1,600	4,800	3.8

Date	Salinity (ppt)	Nitrate as N	Ammonia as N	Phosphorus	Arsenic	Barium	Boron
August 10	6.5			0.7	0.11	0.08	7.8
11	10.0			1.0	.13	.11	13
12	10.0	<0.01	0.11	.8	.12	.11	12
13	13.0			1.0	.17	.10	17
14	9.2	<.01	.02	.8	.15	.07	12
15	5.0			.4	.13	.05	6.8
16	4.1			.4	.11	.05	6.8
17	8.9	<.01	.16	1.0	.14	.11	14
18	9.2			.8	.12	.08	10

Date	Lithium	Molybdenum	Selenium (µg/L)	Strontium	Vanadium	Zinc
August 10	0.40	0.32	1.2	4.0	0.02	0.05
11	.62	.54	1.3	6.2	.02	.07
12	.57	.45	1.2	5.8	.02	.09
13	.76	.67	1.6	7.9	.02	.01
14	.55	.45	1.1	5.7	.02	.03
15	.34	.27	1.1	3.2	.02	.02
16	.38	.38	.9	3.5	.01	.02
17	.67	.67	1.3	7.0	.02	.02
18	.46	.46	1.5	4.9	.02	.02

Table 25. Water-quality measurements for daily composite water samples from D-Line Canal, August 1988

[Concentrations in milligrams per liter except as indicated. All mercury concentrations were below analytical reporting limit. Abbreviations: µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25°C; NTU, Nephelometric turbidity units; ppt, parts per thousand.]

Date	Specific conductance (µS/cm)	Field pH	Onsite mobile lab pH	Turbidity (NTU)	Dissolved oxygen	Calcium	Magnesium
August 10	600	8.6	8.7	4	9.2	30	11
11	490	9.3	9.0	5	10.0	26	11
12	610	9.2	9.0	4	9.5	28	11
13	400	9.2	9.0	3	9.2	26	10
14	425	9.2	8.9	4	10.3	29	11
15	380	9.0	8.1	3	9.8	28	10
16	350	9.0	9.1	6	10.0	27	10
17	445	8.7	8.7	9	9.0	32	10
18	470	9.4	9.3	9	9.9	30	9

Date	Hardness	Sodium	Potassium	Alkalinity	Sulfate	Chloride	Silica
August 10	94	110	9.4	149	110	50	6.9
11	100	110	8.6	156	110	12	7.0
12	110	100	8.3	165	60	50	6.6
13	100	97	8.2	155	56	43	5.9
14	120	110	8.4	157	130	47	5.9
15	110	84	6.3	135	68	40	6.0
16	98	87	6.2	125	47	36	7.2
17	130	96	5.4	174	100	45	7.3
18	110	83	6.5	113	48	45	7.6

Date	Salinity (ppt)	Nitrate as N	Ammonia as N	Phosphorus	Arsenic	Barium	Boron
August 10	0.5			<0.1	0.05	0.06	0.76
11	.4			<.1	.05	.05	.78
12	.5	<0.01	0.10	<.1	.05	.05	.74
13	.0			<.1	.05	.04	.79
14	.2	.01	.04	<.1	.04	.04	.81
15	.1			<.1	.04	.05	.70
16	.0			<.1	.04	.05	.77
17	.0	.01	.05	<.1	.05	.05	.75
18	.1			<.1	.04	.05	.62

Date	Lithium	Molybdenum	Selenium (µg/L)	Strontium	Vanadium	Zinc
August 10	0.06	0.02	0.3	0.37	0.02	0.03
11	.06	.02	.3	.34	.02	.01
12	.06	.02	.3	.36	.02	.01
13	.06	.02	.3	.34	.02	.01
14	.06	.02	.3	.37	.02	.01
15	.05	.02	.3	.34	.01	.01
16	.05	.02	.3	.34	.01	.01
17	.05	.02	.3	.36	.01	.04
18	.05	<.02	.3	.34	.02	.02

Table 26. Water-quality measurements for daily instantaneous water samples from Lead Lake, August 1988

[Concentrations in milligrams per liter except as indicated. All mercury concentrations were below analytical reporting limit. Abbreviations: µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25°C; NTU, Nephelometric turbidity units; ppt, parts per thousand.]

Date	Specific conductance (µS/cm)	Field pH	Onsite mobile lab pH	Turbidity (NTU)	Dissolved oxygen	Calcium	Magnesium
August 10	6,100	8.9	8.8	62	9.2	67	96
11	6,000	8.8	9.2	96	7.2	69	97
12	5,900	8.9	8.9	59	6.8	71	100
13	5,300	8.8	8.8	63	5.6	65	92
14	5,600	8.6	8.8	53	7.1	68	98
15	5,100	8.9	8.8	37	5.7	64	90
16	5,300	8.9	8.9	53	6.9	67	96
17	5,900	8.9	9.0	50	8.5	68	103
18	5,300	8.9	8.9	43	8.6	74	103

Date	Hardness	Sodium	Potassium	Alkalinity	Sulfate	Chloride	Silica
August 10	580	1,000	32	227	430	1,300	6.9
11	570	1,000	32	272	600	1,400	7.5
12	630	1,100	33	257	680	1,200	6.9
13	580	1,000	31	266	400	1,700	6.8
14	600	1,100	33	256	520	1,400	6.8
15	600	980	30	249	470	1,300	6.3
16	610	1,000	31	258	360	1,800	6.4
17	640	1,100	33	258	410	1,800	7.3
18	680	1,100	29	227	560	1,800	5.1

Date	Salinity (ppt)	Nitrate as N	Ammonia as N	Phosphorus	Arsenic	Barium	Boron
August 10	3.5			0.2	0.12	0.14	6.0
11	3.5			.2	.12	.13	5.4
12	3.8	<0.01	0.14	.2	.13	.13	5.6
13	3.2			.2	.11	.12	5.2
14	3.5	.01	.14	.2	.11	.13	5.5
15	4.2			.2	.10	.12	5.0
16	3.1			.2	.11	.13	5.3
17	3.5	.05	.24	.4	.11	.13	5.7
18	3.3			.2	.10	.11	5.4

Date	Lithium	Molybdenum	Selenium (µg/L)	Strontium	Vanadium	Zinc
August 10	0.36	0.11	0.3	1.9	0.02	0.02
11	.36	.11	.3	1.9	.02	.04
12	.37	.12	.3	1.9	.02	.01
13	.34	.11	.3	1.8	.02	.02
14	.37	.12	.3	1.9	.02	.02
15	.34	.11	.3	1.8	.02	.02
16	.36	.11	.3	1.8	.02	.02
17	.39	.12	.3	2.0	.02	.04
18	.34	.13	.3	2.0	.02	.02

Table 27. Water-quality measurements for daily composite water samples from Hunter Drain, August 1988

[Concentrations in milligrams per liter except as indicated. All mercury concentrations were below analytical reporting limit. Abbreviations: µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25°C; NTU, Nephelometric turbidity units; ppt, parts per thousand.]

Date	Specific conductance (µS/cm)	Field pH	Onsite mobile lab pH	Turbidity (NTU)	Dissolved oxygen	Calcium	Magnesium
August 10	12,000	8.3	8.2	14	7.0	190	100
11	13,900	8.4	8.9	7	6.2	220	130
12	27,500	8.5	8.4	37	7.4	350	230
13	22,000	8.8	8.7	13	6.3	380	240
14	25,000	8.7	8.5	8	5.6	390	250
15	8,000	8.7	8.6	14	7.5	160	100
16	410	8.0	8.0	19	8.2	32	10
17	600	8.3	8.2	14	8.4	35	13
18	1,200	8.2	8.3	10	8.8	38	15
Date	**Hardness**	**Sodium**	**Potassium**	**Alkalinity**	**Sulfate**	**Chloride**	**Silica**
August 10	860	3,600	89	223	1,200	4,200	5.0
11	1,100	4,500	110	250	1,300	7,000	13
12	2,300	7,600	180	242	2,000	11,000	14
13	1,800	8,200	200	255	2,900	10,000	13
14	200	8,600	210	276	2,900	13,000	14
15	660	3,200	76	179	1,200	3,700	9.0
16	110	98	4.8	255	52	84	7.6
17	140	180	4.9	124	130	190	6.8
18	170	200	4	102	200	310	6.8
Date	**Salinity (ppt)**	**Nitrate as N**	**Ammonia as N**	**Phosphorus**	**Arsenic**	**Barium**	**Boron**
August 10	9.5			0.6	0.06	0.10	20
11	12			.6	.07	.09	25
12	28	<0.01	0.30	.6	.11	.10	43
13	18			.8	.17	.09	46
14	23	.04	.10	.9	.19	.09	49
15	7.0			.6	.06	.07	18
16	.0			<.1	.02	.08	.81
17	1.0	.05	.15	<.1	.02	.05	1.3
18	1.0			<.1	.03	.05	1.2
Date	**Lithium**	**Molybdenum**	**Selenium (µg/L)**	**Strontium**	**Vanadium**	**Zinc**	
August 10	1.0	0.46	2.2	5.0	0.02	0.09	
11	1.2	.59	2.3	6.0	.02	.06	
12	2.0	1.1	2.1	9.6	.02	.01	
13	2.2	1.2	3.5	10.2	.03	.06	
14	2.3	1.3	3.6	10.4	.02	.01	
15	.86	.47	2.1	4.1	.02	.08	
16	.06	.02	<.3	.39	.01	.02	
17	.08	.04	<.4	.51	.01	.02	
18	.08	.06	.4	.89	.02	.02	

Table 28. Water-quality measurements for daily composite water samples from Stillwater Point Diversion Drain, August 1988

[Concentrations in milligrams per liter except as indicated. All mercury concentrations were below analytical reporting limit. Abbreviations: µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25°C; NTU, Nephelometric turbidity units; ppt, parts per thousand.]

Date	Specific conductance (µS/cm)	Field pH	Onsite mobile lab pH	Turbidity (NTU)	Dissolved oxygen	Calcium	Magnesium
August 10	700	8.4	8.4	39	9.0	48	14
11	550	8.5	8.3	36	8.5	47	14
12	620	8.3	8.4	35	8.4	45	13
13	710	8.4	8.4	32	8.3	51	18
14	470	8.2	8.4	54	8.9	43	12
15	520	8.3	8.3	25	8.7	42	13
16	510	8.4	8.4	37	8.9	43	12
17	580	8.6	8.4	23	9.6	44	13
18	720	8.5	8.5	21	8.4	47	14

Date	Hardness	Sodium	Potassium	Alkalinity	Sulfate	Chloride	Silica
August 10	140	140	8.8	234	130	60	13
11	200	150	8.8	227	140	63	14
12	150	130	8.6	114	120	63	12
13	150	270	13	312	110	58	12
14	150	120	8.6	211	110	50	12
15	150	140	7.9	210	120	55	11
16	140	120	7.7	210	140	55	12
17	160	120	7.3	221	150	43	12
18	160	160	8.6	245	140	48	13

Date	Salinity (ppt)	Nitrate as N	Ammonia as N	Phosphorus	Arsenic	Barium	Boron
August 10	0.5			0.2	0.05	0.07	0.99
11	.5			.2	.05	.07	1.2
12	.5	<0.01	0.21	.3	.04	.07	1.1
13	.8			.3	.04	.06	1.8
14	.5	.05	.50	.2	.04	.07	.86
15	.2			.2	.04	.07	.99
16	.2			.2	.04	.07	.88
17	.2	.04	.44	.2	.04	.07	.91
18	.4			.2	.05	.07	1.1

Date	Lithium	Molybdenum	Selenium (µg/L)	Strontium	Vanadium	Zinc
August 10	0.06	0.03	0.4	0.52	0.02	0.04
11	.07	.03	.5	.51	.02	.06
12	.06	.03	<.4	.48	.02	.05
13	.10	.05	.6	.67	.02	.10
14	.06	.03	.5	.46	.02	.04
15	.06	.03	<.4	.47	.02	.06
16	.06	.03	.5	.45	.02	.07
17	.06	.03	<.4	.46	.02	.04
18	.07	.04	.4	.52	.02	.04

Table 29. Water-quality measurements for daily instantaneous water samples from Stillwater Point Reservoir, August 1988

[Concentrations in milligrams per liter except as indicated. All mercury concentrations were below analytical reporting limit. Abbreviations: µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25°C; NTU, Nephelometric turbidity units; ppt, parts per thousand.]

Date	Specific conductance (µS/cm)	Field pH	Onsite mobile lab pH	Turbidity (NTU)	Dissolved oxygen	Calcium	Magnesium
August 10	2,510	9.1	8.9	410	8.8	35	18
11	1,950	9.0	9.0	580	8.9	24	20
12	1,710	9.1	9.1	390	8.2	35	16
13	2,270	9.1	9.1	280	8.3	26	18
14	2,000	9.1	9.0	200	8.3	30	18
15	2,210	9.2	9.1	260	8.2	22	18
16	1,590	9.1	9.1	190	8.8	36	16
17	1,720	9.0	9.1	240	8.4	31	17
18	2,020	9.2	9.2	170	10.2	28	21

Date	Hardness	Sodium	Potassium	Alkalinity	Sulfate	Chloride	Silica
August 10	160	360	17	261	120	300	11
11	160	480	21	263	240	310	11
12	160	310	15	289	150	310	12
13	150	440	19	298	180	550	10
14	170	410	18	300	140	380	10
15	140	460	20	292	190	480	10
16	170	310	15	291	100	480	10
17	160	340	15	292	190	410	11
18	130	420	18	235	190	450	11

Date	Salinity (ppt)	Nitrate as N	Ammonia as N	Phosphorus	Arsenic	Barium	Boron
August 10	1.7			<0.1	0.09	0.10	2.2
11	1.2			<.1	.11	.11	3.0
12	1.3	<0.01	0.15	<.1	.08	.11	2.3
13	1.5			<.1	.11	.10	2.9
14	1.2	.01	.18	<.1	.10	.10	2.6
15	1.9			<.1	.11	.09	2.9
16	.9			<.1	.08	.09	2.0
17	1.1	<.01	.18	<.1	.09	.09	2.2
18	1.2			<.1	.10	.12	2.7

Date	Lithium	Molybdenum	Selenium (µg/L)	Strontium	Vanadium	Zinc
August 10	0.11	0.05	0.5	0.57	0.03	0.01
11	.12	.07	.6	.55	.03	.01
12	.10	.05	.6	.54	.03	.05
13	.13	.06	.4	.54	.03	.02
14	.12	.06	.4	.55	.03	.01
15	.13	.07	.5	.52	.03	.01
16	.10	.05	.6	.54	.02	.01
17	.11	.05	.5	.53	.02	.02
18	.13	.06	.4	.57	.03	.02