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

Part C. Summary of Irrigation-Drainage Effects on Water Quality, Bottom Sediment, and Biota

By **Ray J. Hoffman**

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Multiply	By	To obtain
acre	4,047	square meter
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
inch (in.)	2.540	centimeter
mile (mi)	1.609	kilometer
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	2.590	square kilometer
ton, short	0.9072	metric ton
ton per day (ton/d)	0.9072	metric ton per day

Temperature: Degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) by using the formula °F = [1.8(°C)]+32. Degrees Fahrenheit can be converted to degrees Celsius by using the formula °C = 0.556(°F-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.

Abbreviated water-quality units used in this report:

µg/L (microgram per liter)
µS/cm (microsiemen per centimeter at 25°C)
Mgal (million gallons)
mg/kg (milligram per kilogram)
mg/L (milligram per liter)
mm (millimeter)

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Abstract

This report presents a summary of the detailed scientific study of Stillwater Wildlife Management Area and other nearby wetlands in west-central Nevada during 1987-90. The work was funded by the National Irrigation Water Quality Program of the U.S. Department of the Interior with the overall objectives of determining (1) the extent, magnitude, and effects of selected water-quality constituents associated with irrigation drainage on fish, wildlife, and human health, and (2) the sources and exposure pathways that cause contamination where adverse effects are documented. Much of the information in this report was summarized from two previously published interpretive reports that were completed to fulfill study objectives. Where applicable, data for the study area from other published sources also were utilized herein.

The results of these studies indicate that the aquatic biota in natural wetlands of the Carson Desert are adversely affected by hydrological and geochemical sources and processes in the Newlands Irrigation Project area. Reactions between water and naturally occurring minerals in the shallow alluvial aquifer increase concentrations of potentially toxic constituents in ground water that eventually enters the wetlands. Once in the wetlands, these constituents are further concentrated by evaporation and transpiration. Water from some agricultural drains that enter Stillwater WMA was acutely toxic to aquatic organisms. The drains in the agricultural area, which eventually discharge to the wetlands, were also implicated as sites of uptake of selenium and mercury by aquatic organisms.

INTRODUCTION

Irrigated agriculture is the most substantial user of water in the western United States. In Nevada, for example, agriculture accounted for 84 percent (2,820 Mgal/d)[1] of the total water withdrawal of 3,350 Mgal/d in 1990 (Solley and others, 1993, p. 11, 37).

For the past decade, irrigation-induced water-quality problems have been of increasing concern to many people. A case in point involves the Kesterson National Wildlife Refuge (NWR) in the agriculturally rich San Joaquin Valley in central California—a precurser to the present study. During 1978-82, increasing amounts of subsurface agricultural drainage were discharged to Kesterson Reservoir in the Refuge. Since 1981, all fish but mosquito fish have vanished from the reservoir. Subsequent analysis of some mosquito fish in 1982 showed anomalously high concentrations of selenium, a trace element[2] (see "Glossary of

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[1] A flow of 2,820 Mgal/d in one year will fill about 34 million standard concrete swimming pools, or cover nearly 3 million football fields with 1 ft of water.

[2] Many elements—copper and selenium, for example—have beneficial nutrient value in trace quantities (<1 µg/L), but in higher concentrations can be lethal to consuming organisms. On the other hand, arsenic, cadmium, lead, and mercury have no known biochemical function and therefore are always considered harmful to an organism.

Selected Terms"), in their tissue. A related follow-up study during the 1983 nesting season at Kesterson NWR revealed high incidences of deformities and deaths of embryos and hatchlings of aquatic birds. The embryonic abnormalities at Kesterson were ultimately linked to a combination of natural and man-induced phenomena, namely the application of irrigation water to soil naturally rich with selenium: selenium was mobilized in saturated soil, then transported to surface water by way of subsurface drainage, to eventually enter the food chain (Presser and Ohlendorf, 1987).

Understandably, the "selenium problem" at Kesterson NWR raised questions about the possible extent of trace inorganic or organic constituents in other areas of the United States that receive irrigation drainage and for which the U.S. Department of the Interior (DOI) has management responsibilities.

The DOI began a five-phase program in late 1985 to identify the nature and the extent of water-quality problems caused by irrigation drainage in the western United States—particularly those areas that receive water from large-scale, Federal irrigation projects (Deason, 1986, p. 203). These irrigation projects were developed during the past century to encourage the occupation and development of the 17 western States, specifically those States west of the 97th meridian.

The five-phase program identified (phase one) Stillwater Wildlife Management Area (WMA) in the Carson Desert (fig. 1), which receives water from the Newlands Irrigation Project in west-central Nevada, as one of nine high-priority sites for initial reconnaissance-level investigation (phase two).

The Newlands Project was one of the first federally funded irrigation projects under the provision of the Reclamation Act of 1902, and the U.S. Bureau of Reclamation began construction in 1903. In 1902, in anticipation of the implementation of the Reclamation Act, about 14,000 acres were cultivated by early settlers who diverted flow to this project from the Carson River (Lee and Clark, 1916). The Newlands Project provides water from both the Carson and Truckee Rivers for irrigation in the Fallon area.

The results of the 1986-87 investigation of Stillwater WMA revealed that potentially toxic trace elements (for example, arsenic, boron, mercury, and selenium) and dissolved solids, which could pose a threat to human health, fish, and wildlife, existed in the wetlands (Hoffman and others, 1990). In addition, the study showed that some of the highest recorded concentrations of trace elements and dissolved solids entering the Stillwater WMA wetlands were in TJ Drain and Hunter Drain.

The studies were funded by the DOI, and were made by a team of scientists from the U.S. Geological Survey and U.S. Fish and Wildlife Service, in cooperation with the Bureau of Reclamation and the Bureau of Indian Affairs.

Because the reconnaissance investigation was not designed to determine cause-and-effect relations, a detailed study (phase three) of the source, transport, and fate of potentially toxic constituents in the area began in water year 1988. The general objective of the detailed study was to determine the extent, magnitude, and effects of selected water-quality constituents associated with irrigation drainage and, where adverse effects are documented, the sources and exposure pathways of known or potentially toxic constituents.[3]

To meet the overall objective of the phase-three detailed study mentioned above, specific technical investigations were designed and conducted for the study area to address the following questions:

1. *How have the natural wetlands changed with respect to the quantity and quality of water resources since the beginning of irrigated agriculture in the mid-1800's?*
2. *What areas contribute the greatest dissolved-solids and trace-element concentrations and loads to receiving wetlands?*
3. *What hydrogeochemical processes are responsible for the mobilization and transport of certain potentially toxic constituents?*
4. *What processes govern aqueous selenium concentrations in drains and wetlands?*
5. *What are the biological pathways of mercury and selenium?*
6. *From a human-health standpoint, what are the mercury and selenium levels of concern in edible parts of ducks?*
7. *Is some drainwater and subsurface water toxic to both freshwater and saltwater aquatic organisms? What chemical agents are responsible for the observed acute toxicity?*
8. *Are mobilized trace elements causing embryonic abnormalities or death of migrating waterfowl?*

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[3] The planned remaining phases, four and five, in the DOI program are to formulate a written plan of action to correct identified adverse effects, then implement the corrective action to eliminate or alleviate the identified problem. Phases four and five are largely the responsibility of the Bureau of Reclamation.

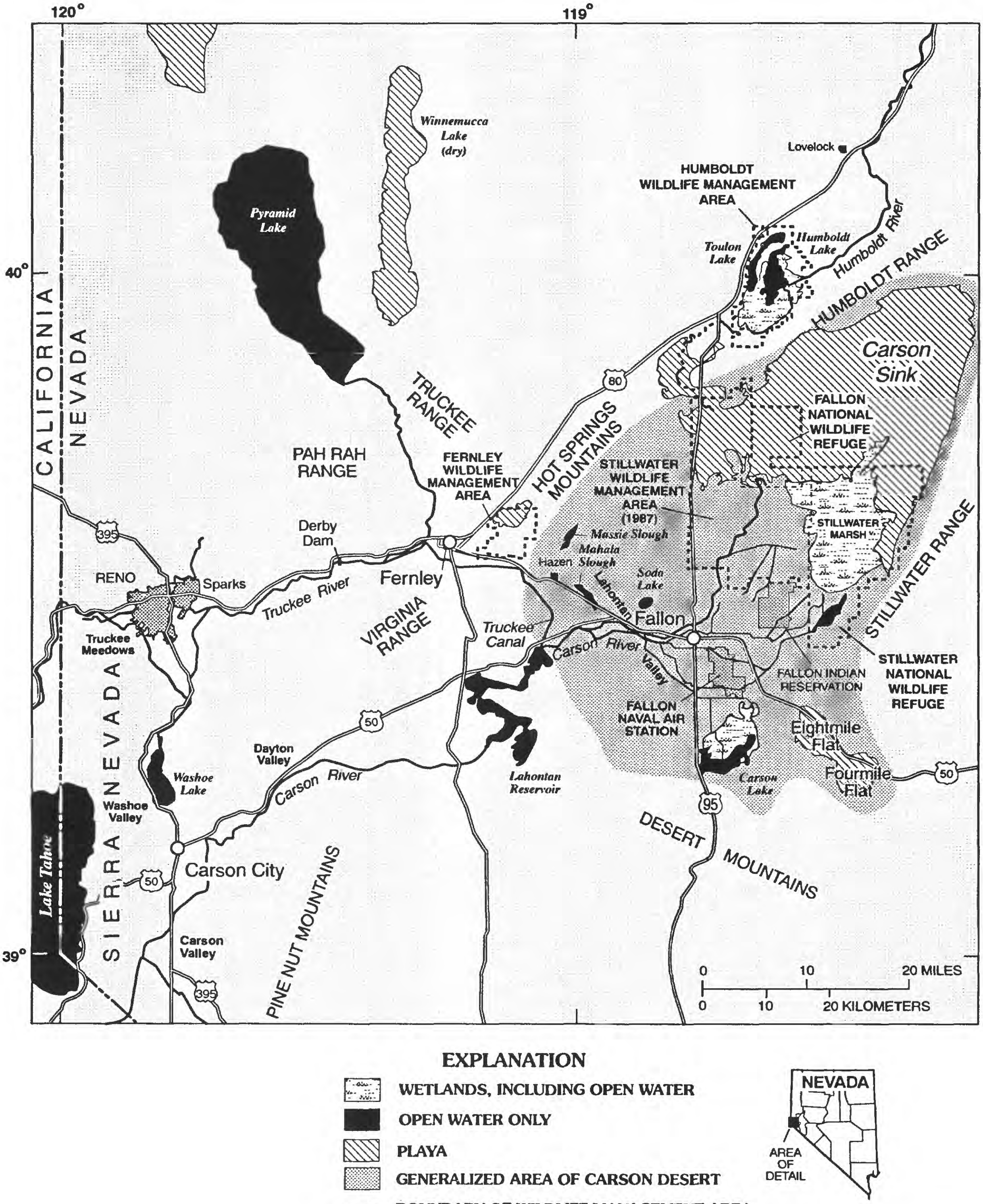


Figure 1. General physiographic features in study area and west-central Nevada.

The detailed study officially spanned water years 1988-90, and involved the collection of physical, chemical, and biological data from agricultural drains and wetlands in and near Stillwater WMA. Data collected by DOI scientists in 1987, however, also were used during the data-interpretation period of the study. Specific information on sampling sites, sampled media, and analytical methods are given in the various reports cited in this document.

This report is intended to give local citizens and water- and wildlife-resource managers a summary of the conclusions from scientific studies of Stillwater WMA and other nearby wetlands during 1988-90 that addressed the eight questions listed above. Much of the information contained herein was derived from reports by Lico (1992) and Hallock and Hallock (1993). Information about the study area from other published sources relevant to the DOI study in Nevada also was utilized in this summary, where applicable.

ENVIRONMENTAL SETTING OF THE STUDY AREA

Physiographic Overview

The study area (fig. 1) lies in the west-central part of the Great Basin, which, as the name implies, is an area characterized by internal drainage; that is, water is discharged to topographic low areas (also known as sumps, or sinks) rather than to the sea. The Carson Desert is the terminal sink for the Carson River, a perennial stream, and infrequently for the Humboldt River when the Humboldt Sink overflows during periods of unusually high runoff from the mountains. The approximately 2,000-mi^2 Carson Desert is nearly encircled by almost a dozen mountains where peak elevations are 1,000-5,000 ft above the lowest point in the area (3,865 ft above sea level in Carson Sink). These stark, mostly treeless mountains are composed of many kinds of igneous, sedimentary, and metamorphic rocks (fig. 2). Included in the Carson Desert are the physiographically important Carson Sink, Lahontan Valley, and Carson Lake.

For purposes of this report, the Carson Sink is defined as the irregular area (especially along the southern margin) encircled by the 3,880-ft topographic contour line (fig. 3). According to Morrison (1964, p. 7 and pl. 1), the water area of the Sink was nearly permanent during the 1800's, inundating nearly 200,000 acres within the 3,880-ft contour. Evidently, the winter floods of 1861-62, 1867-68, 1872, and 1875 maintained high lake levels over a broad area in the topographic lows of the Carson Desert. Maximum water depths in Carson Sink at that time would have been about 10-15 ft. Such an expanse of shallow water in the Carson Desert was not to be seen again for nearly 100 years. The century-plus-old high-water stand was nearly duplicated in October 1984 by inflow of unusually high runoff in the Carson and Humboldt Rivers from 1982 through 1984. Remarkably, the maximum lake level in 1984 was recorded in a false-color satellite (Landsat) image (fig. 4).

Also for the purposes of this report, Lahontan Valley is defined as the area upgradient of the 3,880-ft contour to the 4,100-ft contour (base of Lahontan Dam), exclusive of alluvial fans, pediments, and sinks. Thus, Carson Lake and the Fallon agricultural area—but not Stillwater Marsh—are in Lahontan Valley. Stillwater Marsh is an area of natural wetlands composed of numerous shallow lakes and intervening dry lands in the southeastern part of Carson Sink.

Climate

Most of the study area is classified as mid-latitude desert with cold, breezy winters and hot, windy summers. The high Sierra Nevada range to the west is an effective barrier to the movement of atmospheric moisture eastward. This rainshadow effect allows little precipitation to fall directly in the study area. The average annual precipitation in the Carson Desert is about 5 in. (Dollarhide, 1975, p. 2-3), whereas the average annual evapotranspiration rate is about 60 in., a 12-fold difference (U.S. Bureau of Reclamation, 1987b, p. 2-24). The Carson River headwaters are in the high Sierra Nevada. This vast mountain system usually receives abundant precipitation, mostly in the form of snow, during the winter months. Rising air temperatures during the spring hasten snowmelt runoff to feed much of the annual flow for the Carson and Truckee Rivers.

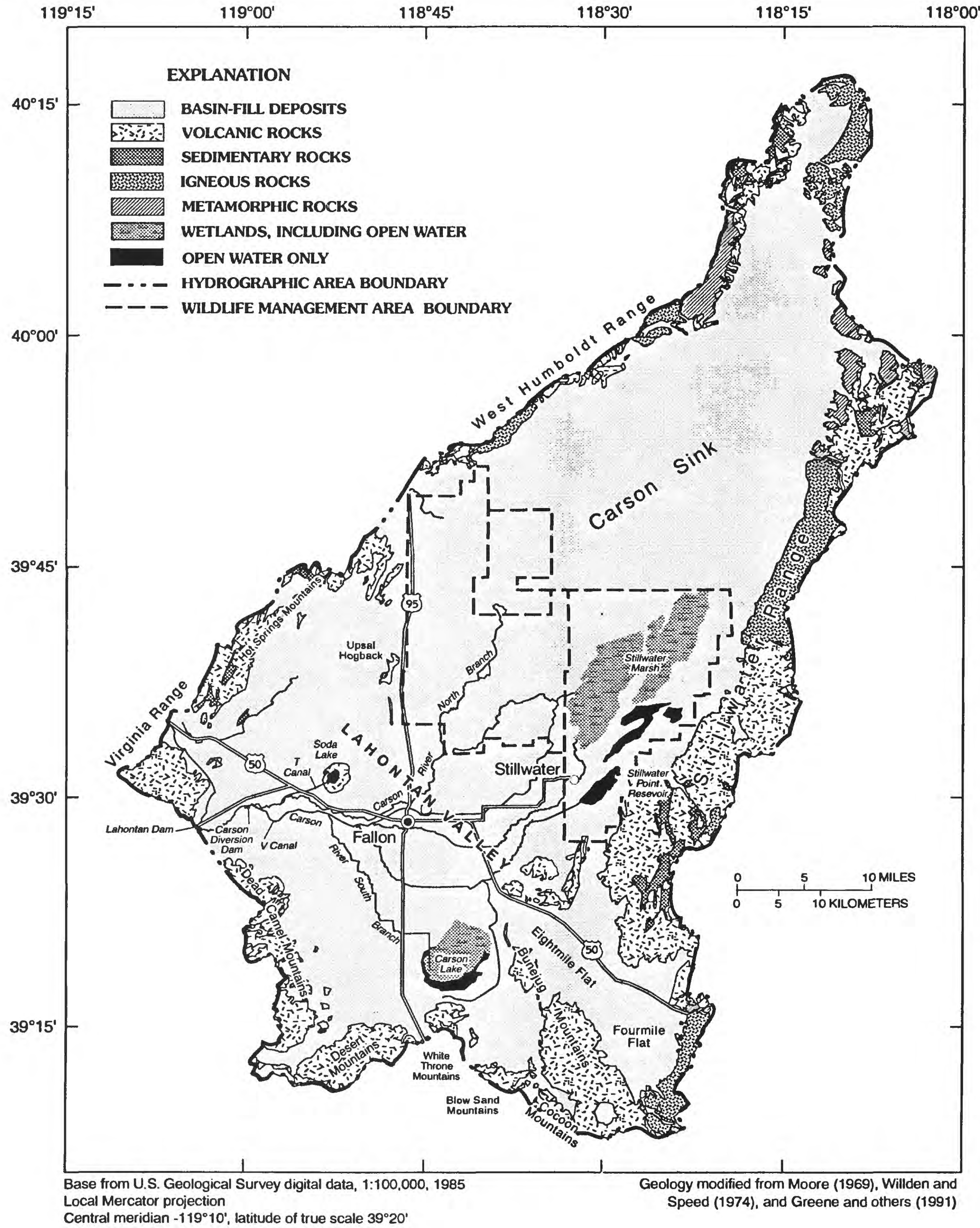


Figure 2. Generalized geology of Carson Desert. Modified from Lico and Seiler (in press).

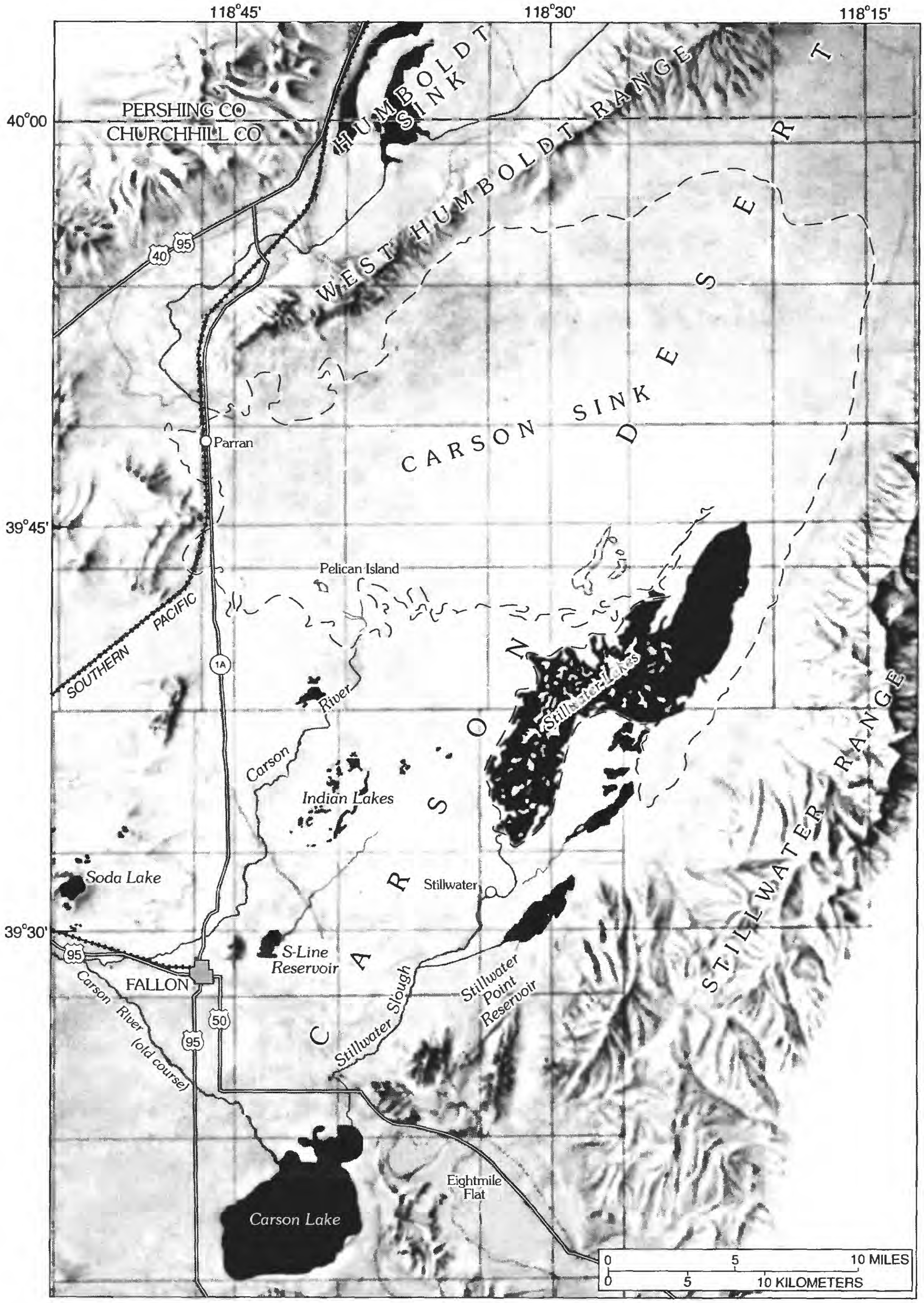


Figure 3. Boundary of Carson Sink at 3,880-foot contour line (dashed). Modified from Morrison (1964, pl. 1).

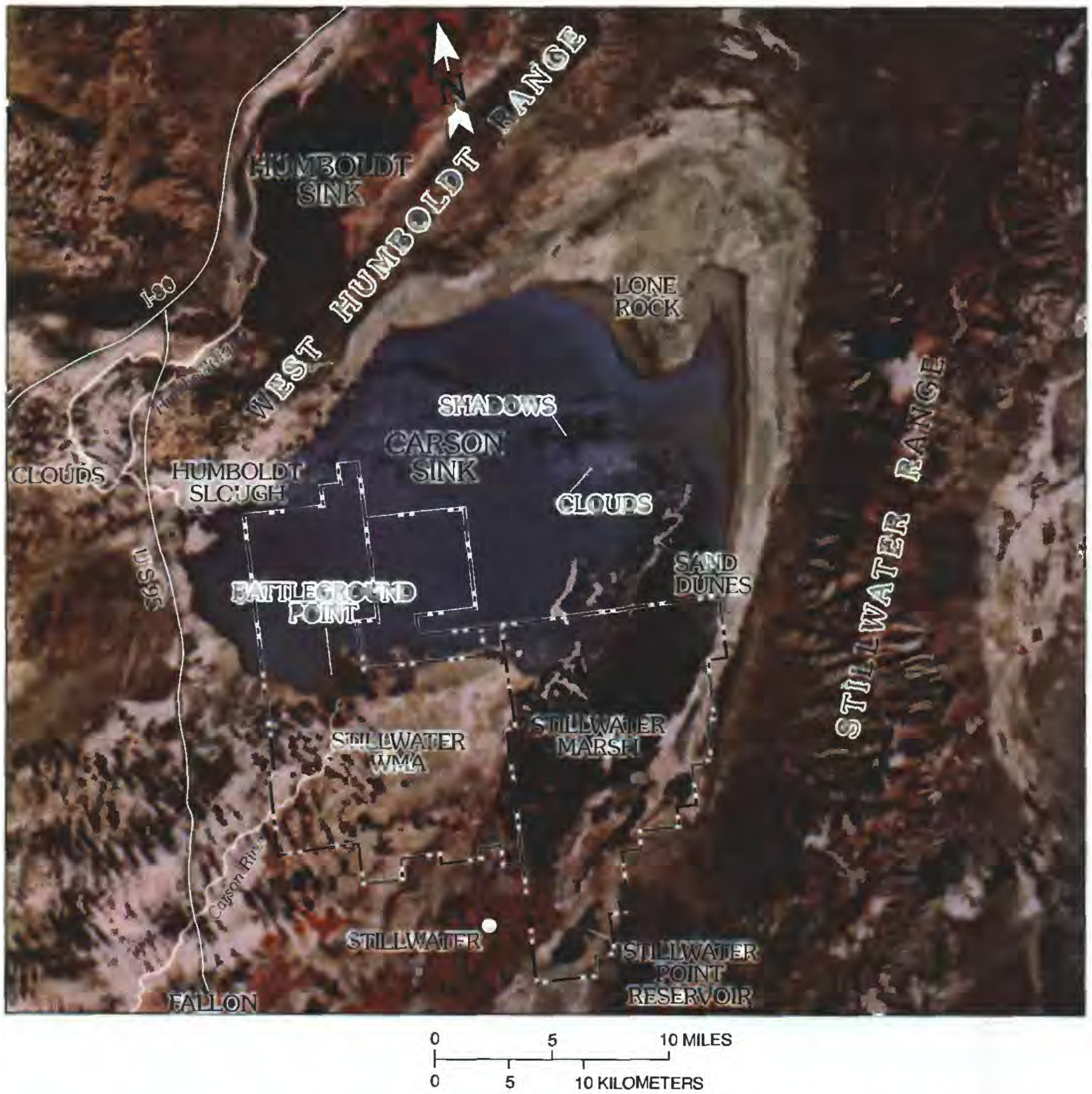


Figure 4. Landsat image of Carson Sink on October 27, 1984, at time of maximum lake level (3,876.2 feet above sea level). Note numerous clouds and their shadows; vegetation appears as various shades of red in this false-color (infrared) image. Abbreviations: WMA, Wildlife Management Area. Source: U.S. Geological Survey, Flagstaff, Ariz.; modified from Rowe and Hoffman (1990, fig. 9).

Soils

Time, climate, and composition of geologic material are the determinants in the formation of soil. Typically, soils that developed during dry climatic conditions are poorly leached. Consequently, sediment that has not been subjected to abundant rainfall tends to be naturally rich in soluble minerals, possibly including high concentrations of trace elements.

In general, the texture of soils of the area ranges from sand to clay, with medium textures predominating; the soil pore water and surface water are typically alkaline. Detailed descriptions of soils in the Fallon-Fernley area are given by Strahorn and Van Duyne (1911), and Dollarhide (1975). In 1987, the U.S. Geological Survey made a study of soil geochemistry of the Carson Desert. These data were presented, without interpretation, by Tidball and others (1991).

Hydrology

The Carson Desert receives water from direct precipitation, Carson River inflow, imported Truckee River inflow by way of the Truckee Canal, Humboldt River overflow (rarely) through the White Plains, and upward flow from deep artesian aquifers. However, direct precipitation is negligible, and the largest component of inflow to the Carson Desert is river water.

Prior to extensive agricultural development in the early 1900's, the Carson River perennially flowed unrestricted into the Carson Desert. Geologic evidence (D.K. Maurer, U.S. Geological Survey, oral commun., 1993) indicates that after entering the Carson Desert, the river changed course many times. For example, during the mid-1800's the Carson River flowed directly southward to Carson Lake; when the capacity of the lake was exceeded, it overflowed northward (by way of Stillwater Slough) to the southeastern part of Carson Sink. In 1862, as a result of spring floods, the river reoccupied an abandoned channel and flowed northward to the southwestern part of Carson Sink. A few years later (around 1867-69), a new, natural channel was cut almost due east that connected with Stillwater Slough, which flowed to the southeastern part of the Sink (fig. 5). The change in the course of the river during the 1800's was due to spring floods (Russell, 1885, pl. VII). Undoubtedly, episodic flooding in prehistorical times also caused the river to change course. Other early maps of the area (Fremont, 1848 [Jackson and Spence, 1970]; Simpson, 1876) show that Carson Lake overflowed to the Carson Sink, presumably by way of Stillwater Slough.

In 1905, as part of the Newlands Irrigation Project, some of the annual flow of the Truckee River was diverted by way of the Truckee Canal, and discharged to the Carson River just downstream from present-day Lahontan Dam. This imported water increased the average annual flow of the lower Carson River by about 60 percent. In 1906, the commingled river water was diverted to the T and V Canals by the newly constructed Carson Diversion Dam on the Carson River (fig. 2). The T Canal essentially serviced the agricultural areas north of Fallon, and the V Canal serviced the areas south of Fallon.

In 1915, major water storage for the Newlands Project was provided by the completion of Lahontan Dam and Reservoir, 4.7 mi upstream from the Carson Diversion Dam. This construction allowed the flow of the Truckee Canal to discharge directly to the reservoir. The stored water is used almost exclusively for flood-irrigation of farmland in the Fallon area. The water is typically released from mid-April to mid-November each year. In wet years, water may be released a month earlier. During the nonirrigation season, no water is released from Lahontan Dam except occasionally as precautionary spills during periods of flooding. A minimal flow, typically less than 5 ft^3/s, seeps from the dam year round. Table 1 shows development and estimated irrigated acreage in the study area from 1855 to 1990.

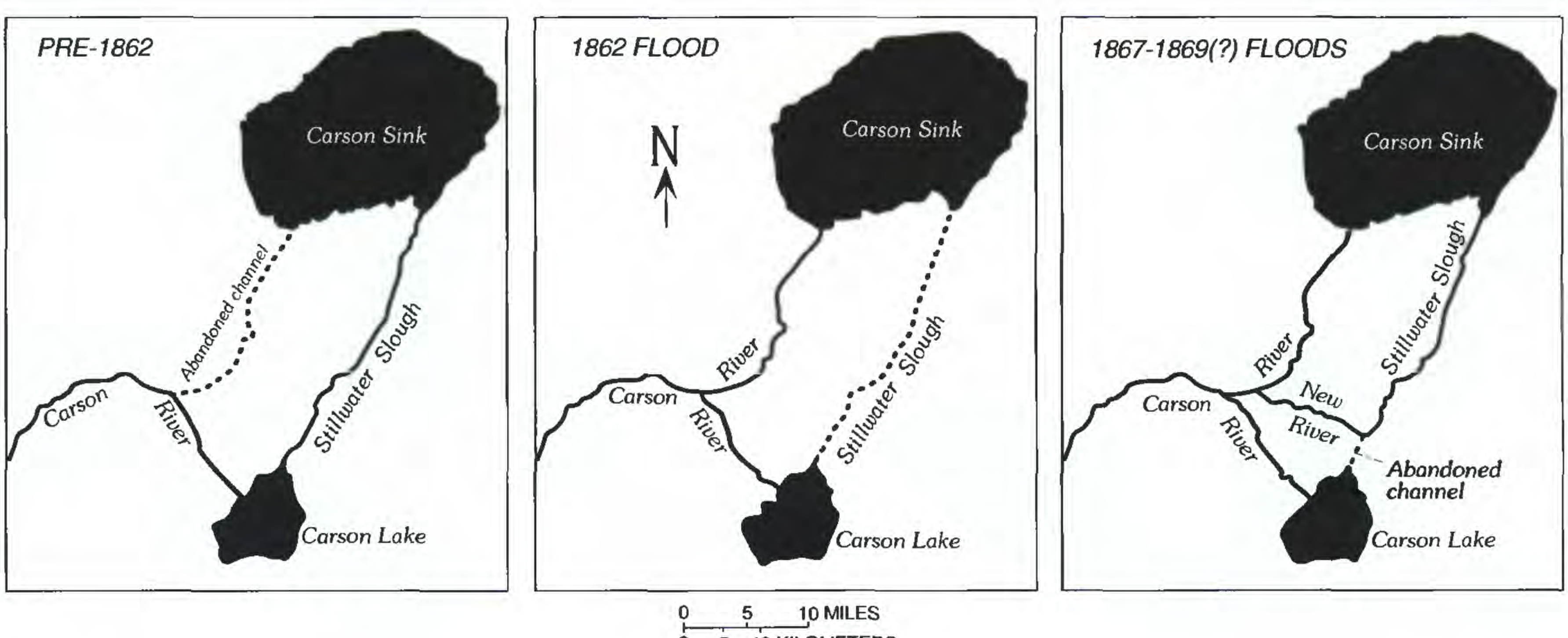


Figure 5. Sketch maps showing changes in flow path of Carson River in Carson Desert from before 1862 to about 1870 (based on written description by Russell, 1885, p. 44-45, pl. VII). Streamflow is generally from left to right.

Table 1. Chronology of development and estimated irrigated acreage in Carson Desert from 1855 to 1990

[Abbreviations: Do., ditto; BOR, Bureau of Reclamation; DOI, U.S. Department of Interior; OCAP, Operating Criteria and Procedures; <, less than.]

Calendar year	Remark	Irrigated acres (rounded)	Source
1855	First non-Native settlers.	<100	Churchill County (written commun., 1986)
1902	Reclamation Act signed.	14,000	Lee and Clark (1916)
1903	Newlands Project began.	17,000	Do.
1905	Derby Diversion Dam on Truckee River built.	19,000(?)	Do.
1906	Carson Diversion Dam built.	20,000	Do.
1909	Average acreage.	29,000	Do.
1911	do.	30,000	BOR (1916, p. 10)
1912	do.	37,000	Do.
1915	Lahontan Dam completed; reservoir filled in 1916.	40,000	Do.
1948	Stillwater Wildlife Management Area established.	52,000	BOR (written commun., 1960)
1965-1984	Winter release of "power" water stopped in 1967.	57,000-67,000	BOR (1986, p. VI-39)
1985	Average acreage.	63,000	Do.
1987	OCAP instituted in 1986.	60,000	DOI (1988, p. 2)
1990	Average acreage.	58,000	BOR (written commun., 1993)

It is important to understand the significance of nearly 80 years of seasonal application of freshwater to alkaline, saline soils over a broad area that, until that time, had received scant moisture. Prior to extensive irrigation in the early 1900's, the river more or less flowed directly to terminal wetlands, and local recharge to the alluvial aquifer was principally along the river channel. But since that time, the river has been virtually removed from its natural channel (at Carson Diversion Dam) and its water widely distributed in a network of numerous canals and laterals to flood-irrigate thousands of acres. Consequently, the shallow ground water is recharged locally by infiltration through irrigated fields and seepage from the many miles of canals and laterals. Poor-quality (high concentrations of dissolved solids) irrigation return flow and—in some places—poor-quality regional ground water, were intercepted by an extensive system of deep, open drains (350 mi at final development) and discharged to wetland habitats. Presently, water to Stillwater Marsh is provided by 6 drains and to Carson Lake by 11 drains.

As a consequence of irrigating parts of the Carson Desert, the shallow ground water in the Fallon area (Lahontan Valley) has risen to near land surface and, in some places, has ponded in wind-blown basins in sand deposits. Inflow of irrigation drainage into these basins gave rise to the Indian Lakes (fig. 3) north of Fallon (Morrison, 1964, p. 7). According to a 1904 water-level map, the depth to ground water throughout Lahontan Valley prior to widespread irrigation in the area, ranged from about 20 to 5 ft below the land surface. From 1904 to 1916, the water table rose 5-8 ft in the area southeast of Soda Lake and about 6 ft in the area northwest of Soda Lake (Lee and Clark, 1916). A 60-ft rise in water level of Soda Lake itself, from 1906 to 1930, was reported by Rush (1972). This rise—also attributable to seepage from flood-irrigated fields and from distribution canals—is a phenomenon peculiar to the lake basin itself and should not be extrapolated to suggest a region-wide rise of similar magnitude in ground-water levels.

Large quantities of salts (for example, sodium chloride) and trace elements probably were flushed from the soil horizon and transported downgradient during the initial years of irrigation from 1906 to 1915 when the number of acres irrigated doubled from 20,000 to 40,000 (table 1). For some insight into the probable load of salts drained from farmland, Hart and Bixby (1922, p. 21) estimated that an unacceptable 87,000 tons of salt per year would be discharged to Carson Lake if the 32,000 acres of land immediately north and northwest of Carson Lake were drained, as was proposed by the local irrigation district. That estimated discharge translates to 2.7 tons of salt per acre per year. Principally because of this forecasted salt load, the proposal was eventually denied. In fact, Hart and Bixby (p. 27) stated that "no reasonable effort should be spared to keep salts out of the Carson Lake since Nature has regarded the area so favorably . . . ." The Bureau of Reclamation drainage plan, instead, was to discharge much of the drainwater from farmland immediately north of Carson Lake by way of the yet-to-be constructed Diagonal Drain, thence to Stillwater Slough—in other words, to the wetlands of Carson Sink.

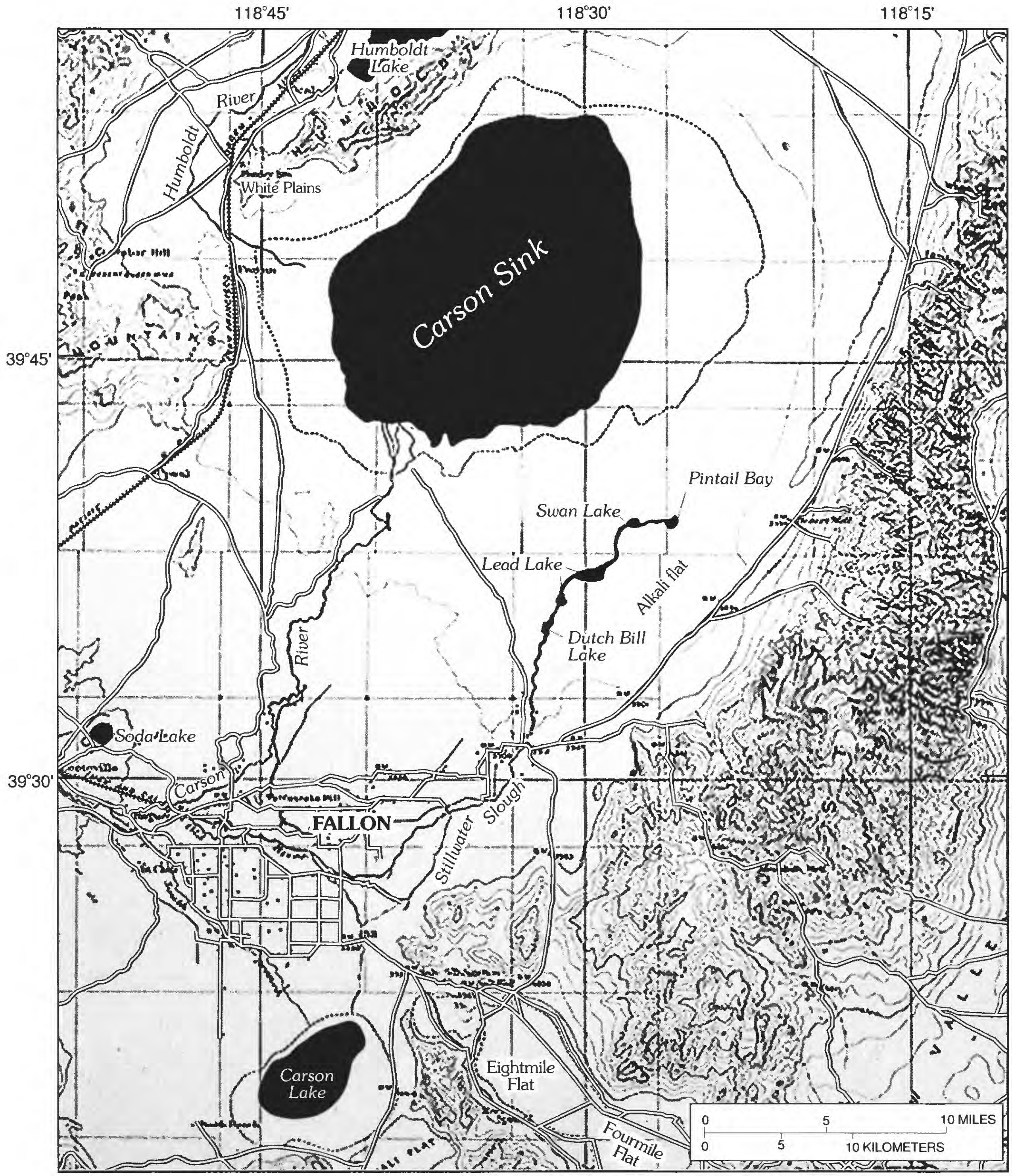


Figure 6. U.S. Geological Survey topographic map of Carson Desert (1908) with modern-day named lakes identified. The 1908 map, with unnamed lakes, scale 1:25,000, was digitized to a scale of 1:100,000. Digitized map was then overlain on a 1979 1:100,000 U.S. Geological Survey topographic map to verify lakes.

According to Morrison (1964, p. 104), the maximum depth of water in Carson Lake would have to be 10 ft in order for the lake to overflow to Stillwater Slough. At its spill altitude (3,919 ft), Carson Lake would inundate about 34,000 acres. The depth suggests a degree of permanence of Carson Lake in former times, thus providing a reliable aquatic habitat in most years for migratory waterfowl along the Pacific Flyway. In 1882, Russell (1885, p. 69) described the lake as having a surface area of about 40 mi^2 (26,000 acres) and a maximum depth of 4 ft.

If the 1908 USGS topographic map of Carson Sink is used as a reference (fig. 6), Stillwater Slough appears at that time to have discharged to a series of unnamed, small, interconnecting lakes. If these lakes were plotted with reasonable accuracy on the 1908 map, the initial, or southernmost, lake is the one presently known as Dutch Bill Lake (in an "island" of private land of the Canvasback Gun Club located within the Stillwater NWR); the second and third are the southern and northeastern parts of Lead Lake (and part of Tule Lake); the fourth is Swan Lake; and the fifth (most downstream), would be Pintail Bay.

Collectively, these natural lakes, including the manmade wetland units (post-1948) in the immediate vicinity, would be referred to later as the Stillwater Lakes (Morrison, 1964), and still later (U.S. Geological Survey topographic map of the Carson sink, 1979, scale 1:100,000) as Stillwater Marsh, the designation used hereafter in this report.

The water table of the shallow alluvial aquifer mimics the shape of the land surface, with average gradients from 6 to 8.5 ft/mi (Glancy, 1986, p. 38). Using published data (Olmsted and others, 1984, p. 23-31; Glancy, 1986, p. 33-41), and an effective porosity of 0.15 (for gravel and fractures), ground-water flow velocities of the shallow alluvial aquifer range from 224 to 82 ft/yr. With an effective porosity of 0.50 (clay), the flow velocities range from 66 to 25 ft/yr. Glancy (1986, p. 33) calculated a flow velocity of 4.5 ft/yr in the basalt aquifer near Fallon. In nearby Fourmile Flat (a playa with gradients from near horizontal to 1.5 ft/mi), ground-water velocity was estimated to be about 16 ft/yr (Desert Research Institute, 1964). These data, although giving some perspective on solute transport rates of conservative constituents in ground water, are to be used with caution. The rates vary greatly from place to place—laterally, as well as vertically—over relatively short distances: one must consider the local land-surface gradients that intercept shallow flowing ground water, and the many possible physical, chemical, and microbiological interactions with a wide variety of aquifer material that can take place along torturous flow paths. The inherently complex and interrelated hydrogeologic environment of the Carson Desert is shown schematically in figure 7.

DISCUSSION OF DETAILED STUDY RESULTS

Evaluation of Historical Wetlands

Quantitative information about the size and ecological condition of the wetlands in the Carson Desert prior to the 1900's is scarce. However, as part of the DOI detailed study, Kerley and others (1993, p. 11) estimated the pre-1900 **average annual** wetland acreage in the principal topographic low areas of the Carson Desert to be about 150,000 acres (27,000 acres in Carson Lake and 120,000 in Stillwater Marsh and other parts of Carson Sink). During times of extended drought or deluge, the total wetland acreage ranged from less than 600 acres, as occurred in 1992 (R.M. Anglin, U.S. Fish and Wildlife Services, oral commun., 1992), to more than 200,000 acres, as seen in 1984 (Rowe and Hoffman, 1990).

According to Kerley and others (1993), the few recorded descriptions of conditions during the 1800's by native Americans and early explorers of the area suggest large areas of luxuriant wetlands that contained a wide variety of aquatic plants. As described, the emergent plants were represented by thick stands of alkali bulrush (*Scirpus maritimus*), hardstem bulrush (*Scirpus acutus*), and cattails (*Typha sp.*) along shallow margins. Today, we know that these tall, hardy plants provide nesting habitat and protective cover for migratory and resident waterfowl, and that the seeds and underground stems (rhizomes) are an important source of food for some ducks and geese, and for muskrats. Cattails are highly sensitive to increased concentrations of dissolved solids. Once reported to be in great abundance, cattails are now found only in scattered patches.

Submergent plants were represented by various pondweeds of varied salinity tolerance, such as sago (*Potamogeton pectinatus*), horned (*Zannichella palustris*), western (*Potamogeton filiformis*), and curlyleaf (*Potamogeton crispus*). These, and other shallow-water plants such as coontail (*Cerataphyllum demersum*), muskgrass (*Chara sp.*), and widgeongrass (*Ruppia maritima*), provide protective cover for fish and succulent food for ducks.

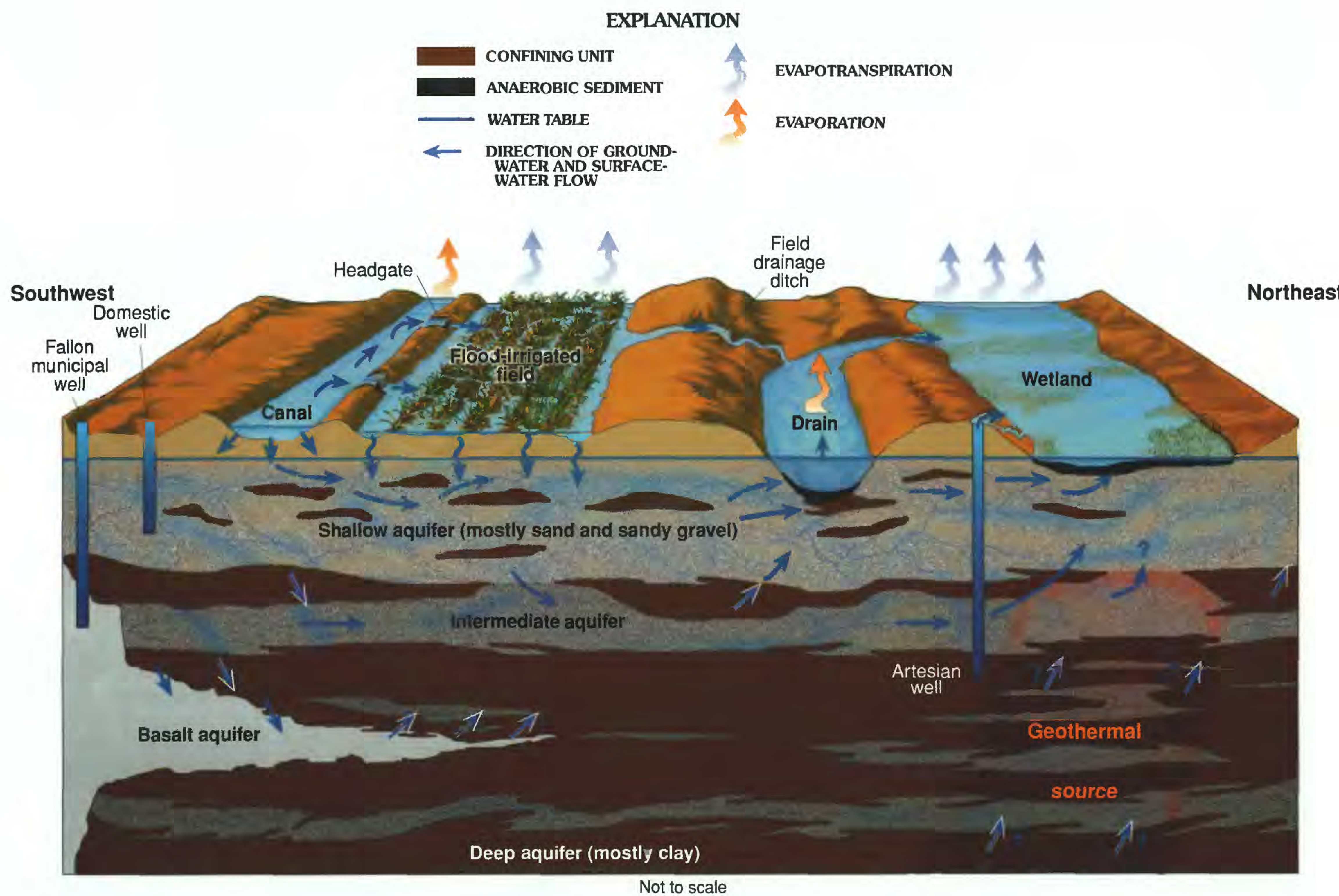


Figure 7. Schematic three-dimensional block diagram showing hydrogeologic features of Carson Desert. Sources: Morrison (1964); Glancy (1986).

Biologists at Stillwater NWR have documented the substantial losses in kind and quantity of emergent and submergent vegetation in both the Stillwater Marsh and Carson Lake areas (Kerley and others, 1993). As an extreme example, since 1905 the wetlands of the Fallon NWR (mouth of Carson River) in the Carson Sink have virtually dried up because of upstream diversions for irrigated agriculture. In recent years (1970-1988), much of the loss of wetland habitat (about 50 percent) has been attributed to the lack of water reaching the wetlands because of court-decreed Operating Criteria and Procedures for delivery of irrigation water (Kerley and others, 1993, p. 19.)

The Operating Criteria and Procedures (OCAP) are a set of rules and incentives to ensure the efficient management of water for the Newlands Irrigation Project in order to resolve longstanding legal disputes concerning the use of Carson and Truckee River waters. A principal goal of OCAP is to reduce the amount of Truckee River water diverted at Derby Dam for use in the lower Carson River basin. In general, this goal is to be achieved principally by (1) maximizing the use of the Carson River and (2) implementing conservation measures to improve the efficiency of the water distribution system of the Irrigation Project (U.S. Department of the Interior, 1988, p. 1-22).

In essence, as project efficiencies increase, the quantity of water delivered to the distribution system also decreases, and so does the volume that reaches the wetlands. The reduction of operational spills from Lahontan Reservoir and at farm headgates also means that less water is available to dilute irrigation return flows. For example, operational spills during 1987 amounted to 65,400 acre-ft, yet the OCAP plan for 1992 and future years is to reduce spills to no more than 35,800 acre-ft (U.S. Bureau of Reclamation, 1987b, p. 1-8)—or a possible 55-percent reduction of freshwater reaching various wetlands in the Carson Desert. Again, as part of the detailed study, Kerley and others (1993, p. 20) estimated that the average concentration of dissolved solids increased seven-fold in drainwater entering Carson Lake, and about four-fold in drainwater entering Stillwater Marsh since the mid-1800's.

Other reductions in biological diversity of the wetlands, as summarized by Kerley and others (1993), include loss of clams, frogs, and certain fish. The loss of fish in the Stillwater wetlands has meant less food to support the colony of American white pelicans (*Pelecanus erythrorhynchos)* on Anaho Island in nearby Pyramid Lake (fig. 1).

Although somewhat speculative, a reasonable assumption can be made that the pre-1900 lakes and intervening marshlands fed by the Carson River supported a diverse assemblage of plants and animals. Over time, many ecological systems undisturbed by man will mature to a complex system of many overlapping and interacting ecological compartments. Such complexity is Nature's way of protecting itself from major (non-catastrophic) disturbances that might quickly destroy a simpler, less mature ecosystem.

Generalized Water Quality and Drainflow

Dissolved solids is a term used to describe the mineral content of natural water. Other terms commonly used interchangeably are total dissolved solids, filterable residue, and salinity. The concentration of dissolved solids is determined by evaporating a known quantity of filtered water to dryness at a specified temperature, and then weighing the remaining residue. A surrogate, and an economical onsite estimate of dissolved solids often used by hydrologists and water-resource managers, is specific conductance. An approximation of dissolved-solids concentration can be determined by multiplying specific conductance by an appropriate constant (Hem, 1985, p. 67). However, given sufficient chemical data for specific water, the relation between the two measures can be more accurately expressed by more accurate coefficients. Hoffman and others (1990, p. 30) and Lico (1992, p. 19) show needed equations for use in Stillwater WMA and vicinity.

Dissolved-solids concentration is a useful measure with which to express the general quality of water. For example, water with a dissolved-solids concentration greater than 1,000 mg/L may be harmful to sensitive crops, and is considered unfit for human consumption. In contrast, the dilute headwaters of the Carson River typically have a dissolved-solids concentration of less than 100 mg/L. Water with less than 500 mg/L may be considered "ideal" for drinking. In general, more than 99 percent of the dissolved-solids concentration in the Carson Desert is composed of major elements, and the remaining less than 1 percent of trace elements.

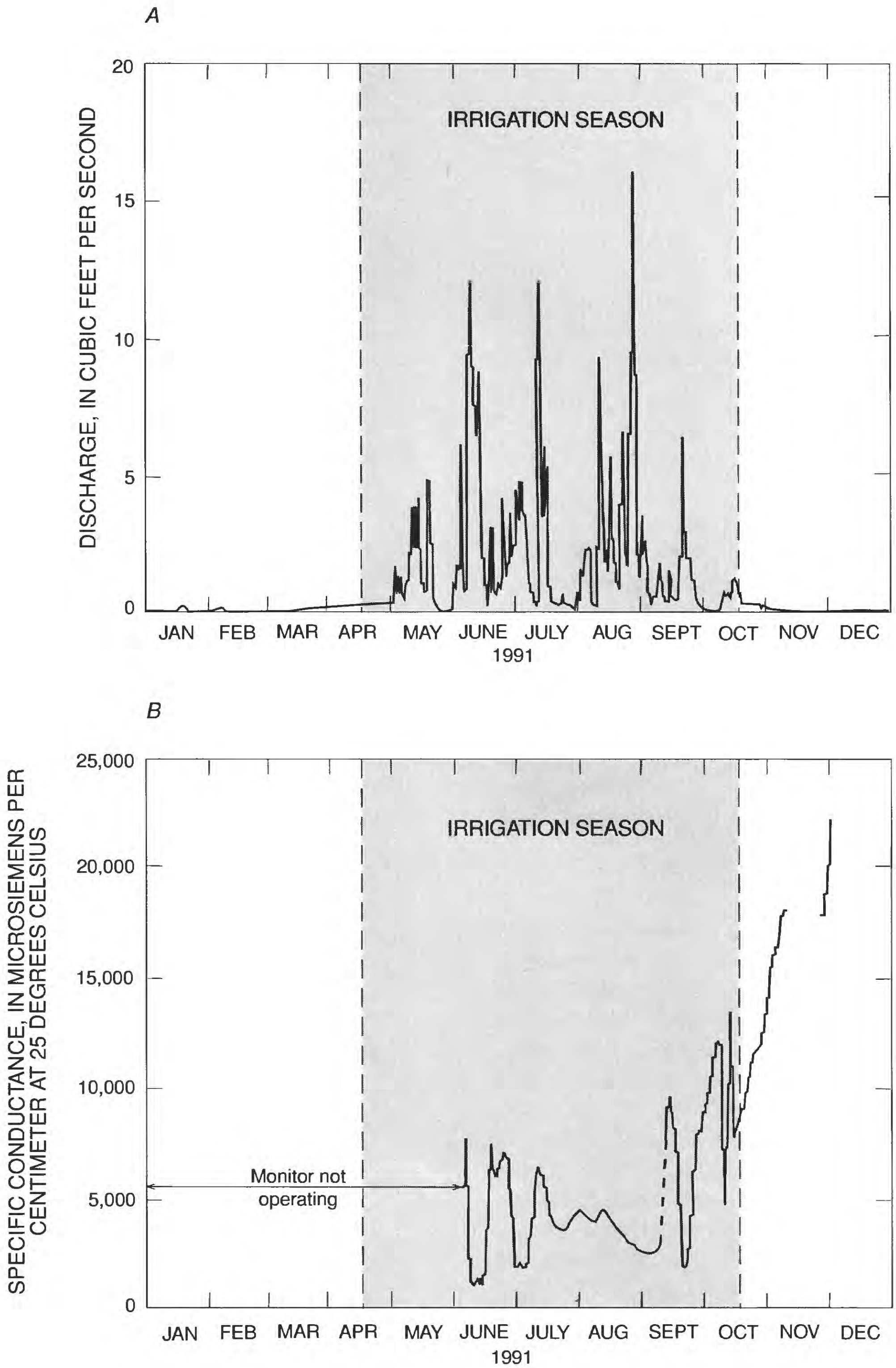


Figure 8. Daily mean (*A*) flow and (*B*) specific conductance of water in Paiute [Diversion] Drain below TJ Drain at U.S. Geological Survey gaging station 10312277 for 1991.

Water of relatively low mineral content (median dissolved solids, about 240 mg/L) is discharged from Lahontan Reservoir for downstream agricultural use in the Newlands Project (Lico, 1992, p. 14). Resultant irrigation drainwater from surface runoff and from the shallow root zone typically contains dissolved-solids concentrations in the range of about 600-3,000 mg/L, a 2.5- to 12.5-fold increase for a typical older drain system (Rowe and others, 1991, p. 97-98). If a drain was so deep as to intercept the more saline regional ground-water flow, then the resulting dissolved-solids concentration might be substantially increased, depending on the prevailing flow regime in the drain. In some instances, drainage water is reused for irrigation purposes, thereby causing further increases in the dissolved-solids content.

Lico (1992, p.15) discusses the extreme variability of drainflow and dissolved-solids concentration (in terms of specific conductance) in monitored drains that discharge to Stillwater Marsh. The variability is particularly pronounced during the irrigation season (April-November). Drainflow during that time commonly represents three main components: irrigation return flow, operational spills, and ground-water seepage. The percentage that operational spills contribute to the total flow is unknown. Drainflow during the nonirrigation season commonly represents year-round seepage of ground water.

For example, recent (1991) monitoring data from a newly established station (USGS site 10312277, Paiute [Diversion] Drain below TJ Drain[4]), substantiate the extreme variability of drainflow (fig. 8*A*) and specific conductance (fig. 8*B*) during the irrigation season. Note that at the beginning of the non-irrigation season (November) specific conductances exceeded 20,000 µS/cm (fig. 8*B*). Drainflow ranged from 0 to 1.2 ft^3/s with brief periods of no flow recorded during the months of January, February, and December 1991; in November 1991, drainflow ranged from 0.01 to 0.10 ft^3/s (Hess and others, 1993, p. 174). Caused in part by prevailing drought (1987-1992), the flow of drainwater to Lead Lake was reduced from 3,000 acre-ft in 1989 to 760 acre-ft in 1991, an overall decrease of 75 percent (data from Rowe and others, 1991, and USGS unpublished data, 1992).

[4] This site is 0.1 mi downstream from the confluence of TJ Drain, and measures the combined flow of Paiute Diversion Drain, D-Line Canal, and TJ Drain.

According to Kerley and others (1993, p. 20), reduction of freshwater supplies and an increase in salts leached from irrigated land have resulted in a seven-fold increase in average dissolved-solids concentration reaching the Carson Lake and a four-fold increase reaching the Stillwater wetlands, when compared with the estimated natural (pre-1900) average. Because of the known positive correlation of boron, sodium, and chloride with dissolved solids from the study area (Hoffman and others, 1990, p. 35, 36; Lico, 1992, p. 37), a corresponding increase in the concentration of these elements can be predicted with increased concentration of dissolved solids. The elevated concentrations of these elements singly or in combination with other properties of drainwater are suspect in the apparent large loss of emergent vegetation (cattails) and moderate loss of submergent plants (sago pondweed) in the Stillwater and Carson Lake wetlands. The loss of primary producers (plants), the base of the food chain, usually has a negative effect on higher trophic levels, both in terms of loss in nesting or cover habitat, and in loss of food supply. During the past three decades, Federal and State wildlife biologists have observed that migratory waterfowl have decreased in kind and number; freshwater clams, frogs, and turtles—once found in abundance in the study area—are virtually gone; river otter and mink have disappeared; and game fish no longer flourish in the terminal wetlands.

The load of dissolved solids is the product of water discharge multiplied by the concentration of the substance of concern. The load of anything in water, whether it be sediment or selenium, can be surprisingly large even for low concentrations if the corresponding water discharge is high. During a flood, the concentration of a potential toxicant may be diluted to such an extent as to be completely nontoxic: an exceptionally large quantity of freshwater can simply overwhelm the amount of material, suspended and dissolved, which it carries. Once that water enters an impoundment or wetland with no outlet, the water evaporates over time, and the solutes become concentrated to the point of being initially physiologically stressful, and subsequently acutely toxic to most plants and animals. In fact, such a sequence, compounded by freezing temperatures, occurred in the study area during 1986-87 (Rowe and Hoffman, 1990).

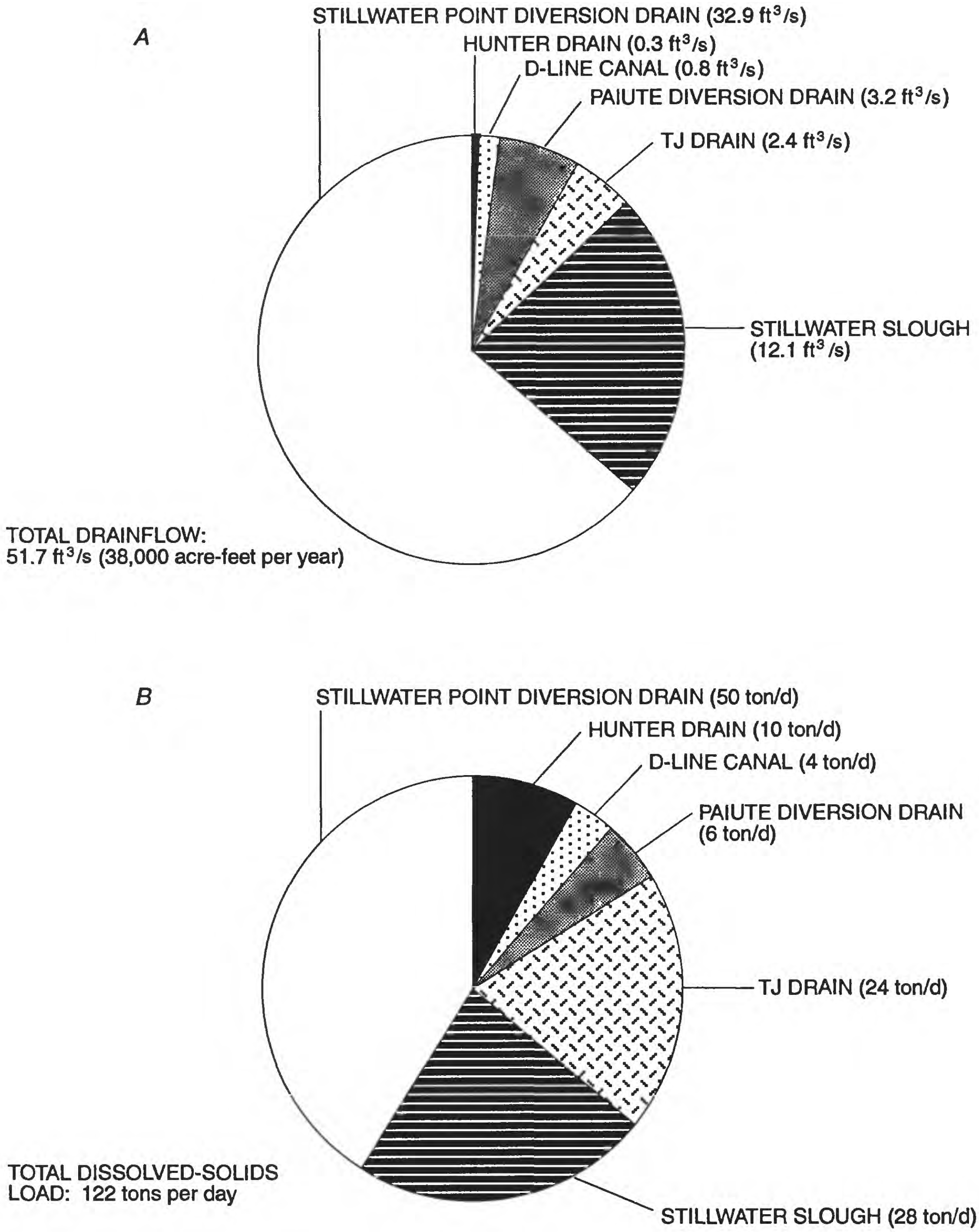


Figure 9. Daily mean (*A*) flows, in cubic feet per second (ft^3/s) and (*B*) dissolved-solids loads, in tons per day (ton/d) in agricultural drains entering Stillwater Marsh, 1986-89.

The diagrams in figure 9 show the quantity of drainflow and the load of dissolved solids in the six agricultural drains entering Stillwater Marsh in 1989 (fig. 10). Of the six drains, both TJ Drain and Hunter Drain contained the highest recorded concentrations of dissolved solids and potentially toxic trace elements in the study area (Hoffman and others, 1990; Lico, 1992; Tokunaga and Benson, 1991). Furthermore, tests of water samples from these two drains indicated acute toxicity to test organisms, including a salt-tolerant fish (Finger and others, 1993; Ingersoll and others, 1992; Dwyer and others, 1992). Although TJ Drain and Hunter Drain together contributed only 2.7 percent of the total flow to the wetlands, compared to other drains (fig. 9*A*), their combined dissolved-solids load was significant (28 percent of the total; table 2).

The largest contributor of dissolved-solids load to Stillwater NWR was Stillwater Point Diversion Drain (table 2). This drain, however, not only serves the largest area, in terms of drainage, but also receives treated municipal sewage effluent from the Fallon area. In terms of concentrations of selected trace elements, Stillwater Point Diversion Drain had the following ranges: arsenic, 59-120 µg/L (median 74, n=5); boron, 840-4,000 µg/L (1,700, n=5); lithium, 51-90 µg/L (66, n=5); mercury, all less than 0.1 µg/L (n=5); molybdenum, 23-83 µg/L (40, n=5); and selenium, all less than 1.0 µg/L (n=5).

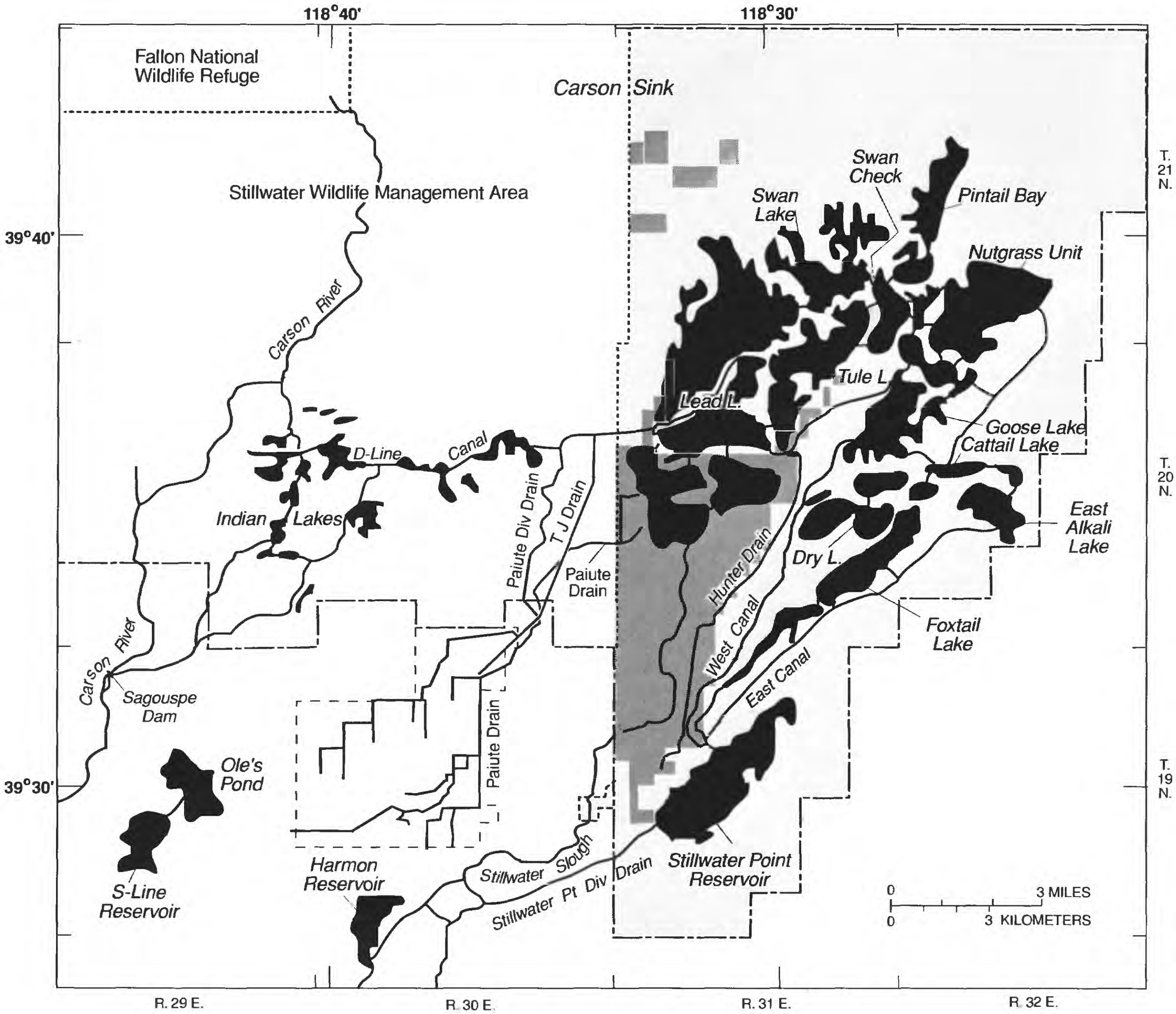
During normal runoff years, the wetlands at the terminus of the Carson River are natural evaporation pans which retain all of the incoming salts. Thus, in such areas of internal drainage and with high evapotranspiration rates that tend to concentrate dissolved solids, chemical loads can be important. Historically, the wetlands typically received its annual flow in a seasonal pattern dominated by dilute snowmelt runoff in early spring. Maximum runoff commonly occurred in May and June, as recorded upstream by active gaging stations on the East and West Forks of the Carson River. Runoff from April through July accounted for about 40-60 percent of the total annual flow (Glancy and Katzer, 1976, p. 34). In most years, the maximum flows just described commonly flushed the initial wetlands of accumulated dissolved solids. Today, however, the annual runoff pattern in the lower Carson River is modified by Lahontan Dam, whereby runoff is stored in Lahontan Reservoir and subsequently spread throughout the 6-7 month irrigation season. The wetlands, in turn, are managed to maximize the retention of available water—principally irrigation return flow. That is, the freshest water available is delivered to an initial wetland unit, such as Lead Lake or Dry Lake. When the dissolved-solids concentration nearly doubles in the initial unit because of evapotranspiration, the water is flushed to a secondary wetland unit, such as East Alkali Lake, which sustains more salt-tolerant aquatic life and where the dissolved-solids concentration again nearly doubles. This water is subsequently flushed to a downstream tertiary wetland (such as Pintail Bay). Lastly, when the dissolved-solids concentration exceeds 28,000 mg/L, the water is discharged from the tertiary unit to evaporate as wastewater on the open playa.

In summary, water that reaches the Stillwater Marsh today is a mixture of water from three sources: surface water, ground-water seepage, and—less importantly—direct precipitation (fig. 7). Surface-water flow is derived from occasional operational spills (freshwater) and from overland runoff (tail water) from flood-irrigated fields. Ground-water flow represents discharge from the shallow alluvial aquifers and recharge from application of irrigation water to agricultural fields and from seepage from the delivery system. The deep, open drains are discharge points from the shallow aquifers.

Table 2. Dissolved-solids loads entering Stillwater Marsh from drains servicing the agricultural area, 1986-89

Agricultural drain[1]	Dissolved-solids load (percent of total)
Stillwater Point Diversion Drain	41
Stillwater Slough	23
TJ Drain	20
Hunter Drain	8
Paiute Diversion Drain	5
D-Line Canal	3
TOTAL	100

[1]In order of decreasing load.



EXPLANATION

- **OPEN WATER**
- **STILLWATER NATIONAL WILDLIFE REFUGE** — As defined July 1990. Western boundary is dotted line
- **PRIVATELY OWNED LAND WITHIN REFUGE** — Includes Canvasback Gun Club
- - - - **BOUNDARY OF FALLON INDIAN RESERVATION** — North boundary coincides with that of adjacent Wildlife Management Area

Figure 10. Locations of drains, including Stillwater Slough, entering Stillwater National Wildlife Refuge, and other important hydrologic features.

Hydrogeochemical Processes

To shed light on the puzzling variability of trace-element concentrations (other than mercury) in the geohydrologic system, a detailed examination of the occurrence, distribution, and processes responsible for mobilization and transport of potentially toxic constituents was made in the lower TJ Drain/Lead Lake system in Stillwater WMA (fig. 10). Elevated concentrations of some potentially toxic trace constituents, namely arsenic, boron, mercury, and selenium, in either water, bottom sediment, or biota, or in a combination of the three, were reported by Hoffman and others (1990). Other elements of concern, of which little was (and is) known biochemically, were lithium and molybdenum (Finger and others, 1993, p. 37)—and perhaps uranium (Hoffman and others, 1990, p. 37, 76; Lico, 1992).

High concentrations of the above-mentioned elements were not found in all sampled media, nor were high concentrations found at every sampling site. Furthermore, the concentrations of some constituents, particularly selenium and mercury, in most samples of filtered surface water were at or below analytical reporting limits. Because of the known affinity of mercury for sediment particles, high concentrations of mercury were not expected in filtered water samples. The study area is widely contaminated with mercury-bound sediment (Tidball and others, 1991) as a result of historical ore-milling operations upstream in the mid-1800's, but the elevated concentrations of mercury virtually predated the Newlands Irrigation Project (Hoffman and others, 1990, p. 43).

TJ Drain/Lead Lake System

Although other agricultural drains entering Stillwater WMA were examined as part of the DOI detailed study, TJ Drain and Hunter Drain were emphasized in the present report because the water contained high concentrations of trace elements and dissolved solids, and was found to be toxic to aquatic animals. TJ Drain was constructed in the early 1980's to provide subsurface drainage from irrigated and non-irrigated parts of the Fallon Indian Reservation. After flowing northward about 6 mi, water from TJ Drain mixes with water in Paiute Diversion Drain, which in turn flows to Lead Lake.

One of the important results of the detailed study was a description of the processes that appear to control major- and minor-element composition: dissolution of aquifer materials by secondary recharge, such as irrigation water, contributes arsenic, boron, molybdenum, uranium, and vanadium to ground water (Lico, 1992, p. 42). As mentioned earlier, trace-element-rich sediment deposits are widely distributed naturally in an arid, closed-basin environment. Furthermore—as with selenium—molybdenum, uranium, and vanadium are readily mobilized and transported in oxygenated, alkaline water—a common occurrence in the study area. Such an environment also favors the formation of ferric (oxy)hydroxide (Lico, 1992, p. 35), which has a lower adsorptive capacity for arsenic at higher pH relative to more acidic water. This reduced adsorptive capacity at elevated pH is consistent with the tendency for slightly alkaline, nonthermal ground water to have elevated concentrations of soluble arsenic (Welch and others, 1988, p. 338). Boron is highly mobile over a wide range of pH and oxidation-reduction conditions. Whereas the concentrations of some trace elements were relatively high in the shallow ground water, selenium was at or below the analytical reporting limit. Arguably, selenium has a more random distribution pattern in ancient Lake Lahontan sediment than the other trace elements commonly found in high concentrations.

Probably reflecting the influence of poor-quality ground water, TJ Drain (and Hunter Drain) during 1987-90 contained some of the highest recorded concentrations of potentially toxic trace elements, namely dissolved arsenic, boron, lithium, molybdenum, and selenium of any drain sampled (Tokunaga and Benson, 1991; Lico, 1992; Finger and others, 1993).

Using stable isotopes of sulfur and carbon in 1987-88, Lico (1992) determined that, during the irrigation season, TJ Drain water near its mouth (most distal part of the TJ-Drain system) is a mixture of irrigation return flows and ground-water seepage, and that during the nonirrigation season ground water seepage is the dominant source.

In 1988, Finger and others (1993) found the following range of concentrations (all dissolved) in water samples collected from TJ Drain: arsenic, 1,100-1,700 μg/L (median 1,300 μg/L, n=9); boron, 6,800-16,700 μg/L (11,900 μg/L, n=9); lithium, 340-760 μg/L (550 μg/L, n=9); molybdenum, 270-670 μg/L (450 μg/L, n=9); and selenium, 0.9-1.6 μg/L (1.3 μg/L, n=11). Mercury concentrations were all below the analytical reporting value of 0.3 μg/L (n=11).

For 1987-89, Rowe and others (1991) reported the following range of concentrations (all dissolved): arsenic, 48-230 μg/L (median 190 μg/L, n=6); boron, 6,900-25,000 μg/L (13,500 μg/L, n=6); lithium, 320-810 μg/L (440 μg/L, n=6); molybdenum, 270-950 µg/L (440 µg/L, n=6); selenium and mercury were all below the analytical reporting level of 1.0 µg/L and 0.10 µg/L, respectively. All reported selenium concentrations in the water were below the Nevada aquatic life criteria for acute toxicity (20 µg/L), and for chronic toxicity (3-day average not to exceed 5 µg/L; Nevada Bureau of Health Protection Services, 1992).

And during 1989-90, Tokunaga and Benson (1991) recorded the following range of concentrations (all dissolved) for TJ Drain: arsenic, 20-470 µg/L (median 103 µg/L, n=15); boron, 600-23,000 µg/L (9,400 µg/L, n=15); molybdenum, 400-8,400 µg/L (700 µg/L, n=3); and selenium, 0.2-4.2 µg/L (0.8 µg/L, n=15). No data were reported for mercury and lithium.

The variation in drainwater data presented above reflect differences due to variations of flow, time of sampling, sampling techniques, and analytical methods.

Hunter Drain

Hunter Drain, constructed in 1949, extends northward about 7 mi from near Stillwater Point Reservoir to a recent (1989) manmade evaporation pond just southeast of Lead Lake (fig. 10). Prior to 1989, Hunter Drain discharged to Lead Lake. Flow of Hunter Drain probably represented ground-water seepage attributable to a rise in the water level of nearby Stillwater Point Reservoir. Because of the apparent rise in the local water table, Hunter Drain was deepened in 1958 to intercept shallow ground water that otherwise would have flowed to the privately owned Canvasback Gun Club. Hunter Drain is substantially deeper than the two near-parallel canals that distribute water from Stillwater Point Reservoir to other wetlands in the Refuge. When the water level in the Reservoir was later lowered in 1990, seepage to Hunter Drain nearly ceased.

Selenium concentrations of 15 and 21 µg/L were found at sites in Hunter Drain in March 1989 (Rowe and others, 1991, p.111). Finger and others (1993) found dissolved selenium in the drain ranging from less than 0.3 to 3.6 µg/L (median 2.1 µg/L; n=9). During 1989-90, at a number of sites along Hunter Drain, Tokunaga and Benson (1991, p. 37) found dissolved selenium ranging from 4.9 to 97 µg/L (median 8 µg/L, n=16). Both the acute and chronic selenium criteria for aquatic life were exceeded in Hunter Drain. Samples of unfiltered water from Hunter Drain consistently yielded concentrations of selenium 1-2 µg/L higher than corresponding filtered samples (Tokunaga and Benson, 1991, p. 37). Arsenic, boron, lithium, molybdenum, and dissolved-solids concentrations were extremely high (Rowe and others, 1991, p. 104-113), probably reflecting seepage of poor-quality ground water.

Lico (1992) offers a plausible explanation for the high concentrations of potentially toxic constituents found in drainwater: as oxygenated, irrigation water of low dissolved-solids content infiltrates into the shallow aquifer, it dissolves the sediment matrix and associated naturally occurring trace elements, thus increasing the concentration of solutes. As water moves down the flow path, dissolution and desorption processes predominate under oxidized and alkaline conditions to further increase solute concentrations in ground water. The reaction of water with the solid phase is facilitated by the coatings on the buried fine-grained sediment particles. Farther down the flow path, near the area of ground-water discharge, the concentration of solutes in the shallow aquifer is increased even more by evapotranspiration (ET). As discussed by Lico (1992, p. 45), ET is the dominant process by which solutes are concentrated in ground water near ground-water discharge areas; the list of factors that cause high ET includes a shallow water table, plentiful plants with roots that tap the water table (phreatophytes), high air temperature, and wind. Concentrating effects due to ET on or in irrigated fields is important, too. The chloride data reported by Rowe and others (1991, p. 96-99) indicate that ET processes on agricultural land may increase solutes from two- to four-fold.

Both the material and the mechanisms to mobilize salts and trace elements within the Carson Desert described by contemporary studies, such as Lico (1992), were present in the past, and will continue to be present in the future. Naturally occurring salts and trace elements in the desert soils are mobilized by application of irrigation water. Soluble elements in transit can be intercepted by shallow drains during the initial dewatering phase (lowering of water table below the root zone) and discharged to wetlands. Deep drains that receive seepage from saline ground water all year, such as TJ and Hunter Drains, are also responsible for the discharge of salts and contaminants to the wetlands by way of the manmade surface conduits.

Water from Hunter Drain is chemically similar to the ground water near TJ Drain. During 1987-89, periodic streamflow measurements were made in Hunter Drain during the irrigation season (Rowe and others, 1991, p. 93). Flow at site 35 was commonly less than 1 ft^3/s and probably represented seepage of ground water. A series of field measurements was made by the U.S. Geological Survey at 11 sites along the 7-mi reach of Hunter Drain from 7 a.m. to 2 p.m. on March 30, 1987, just prior to the irrigation season. Water samples were collected at four sites along the drain. The data showed that the specific conductance of 120,000 µS/cm of ground water seeping into the drain at the "headwater" site had decreased 41 percent (to about 70,000 µS/cm) at the discharge point (a sump) 7 mi downstream. The decrease in dissolved-solids concentration was probably a result of dilution by inflow of less-saline seepage along the reach: the flow along the drain increased from barely perceptible (<<0.01 ft^3/s) at the headwater site to a measured 0.04 ft^3/s at the most downstream site.

During the seepage run, dissolved boron concentrations decreased in the downstream direction from 260,000 µg/L to 60,000 µg/L and lithium from 8,500 µg/L to 2,700 µg/L. Molybdenum increased from 5,000 µg/L to 56,000 µg/L at the mid-reach site and then decreased to 2,500 µg/L at the most downstream site. Dissolved selenium was 15 and 21 µg/L at the two upstream sites, then decreased to the analytical reporting limit of <1 µg/L farther down the drain. The concentration of dissolved arsenic (200 µg/L) stayed relatively constant along the drain.

The dramatic decrease in soluble selenium in Hunter Drain probably resulted from biological uptake of selenium by periphytic algae that coated much of the bed in this shallow drain (water depth less than 3 in.). For example, the selenium concentration in 12 samples of periphytic algae collected six times from February 1988 to July 1989 near the downstream sampling site, ranged from 5.53 to 0.87 µg/g, dry weight, with a median of 3.4 µg/g (Rowe and others, 1991, p. 156). The median selenium concentration in algae from Hunter Drain was substantially greater than concentrations recorded in algae from other major drains to the Refuge (R.J. Hallock and others, 1993a, fig. 13), and about three times greater than in algae from sites unaffected by irrigation drainage. The median arsenic concentration in the periphytic algae at the most downstream site in Hunter Drain was a relatively high 37 µg/g.

As mentioned above, deep drains—such as TJ and Hunter—serve as discharge points for poor-quality, shallow ground water. In addition, most drain bottoms contain a thick layer of anaerobic sediment. Anaerobic sediment is known to be an effective scavenger of many trace elements, including selenium. In fact, removal of selenium (as mobile selenate) from water and immobilization in anaerobic sediment (as elemental selenium) by bacteria has been suggested as a novel bioremediation technique (Gerhardt and others, 1991; Long and Morgan, 1990). However, recent research on anaerobic sediment in saline environments—including sites in the Carson Desert—has shown that nitrate inhibits the selenate-reduction process (Oremland and others, 1990; Steinberg and others, 1992). Evidently, in the presence of nitrate and selenate, other factors being equal, selenate-reducing bacteria prefer nitrate as the electron acceptor, thereby transforming nitrate to molecular nitrogen (N_2) and leaving selenate untransformed.

Nitrate-rich ground water is common in the study area (Whitney, in press). Therefore, if bioremediation of selenium were planned, the water would have to undergo nitrate removal before selenate reduction could occur.

Inhibition of selenate reduction in the presence of nitrate also may present a mechanism that allows selenate in ground-water seepage to pass unimpeded though anaerobic drain-bottom sediment. Such a mechanism may explain, in part, the elevated selenium concentrations in TJ Drain and Hunter Drain. Once in an open drain, dissolved selenium is readily available for biologic uptake.

In addition to favoring the selenate species of selenium, the oxidation-reduction potential of shallow ground water and surface water in drains favors the arsenite species of arsenic, an extremely toxic oxyanion in water. The Nevada acute-toxicity criterion for arsenic (as arsenite) for the protection of aquatic life is 360 µg/L. Unfortunately, arsenic **species** were not measured in drainwater, but water samples from the shallow ground water in eight observations wells near Lead Lake were analyzed for arsenite during the 1987-90 detailed study. The results show that water from three of eight wells exceeded the Nevada aquatic-life criterion of 360 µg/L with concentrations of 390, 480, and 1,000 µg/L dissolved arsenite (Rowe and others, 1991, p. 196).

Effects on Biota

Toxicity Tests

Toxicity testing can be a meaningful investigative technique when used with other appropriate environmental data. A chemical analysis of water alone will not show definitively that a chemically complex water sample is toxic to any organism, because of the many possible antagonistic or synergistic effects among the chemicals and the differences in toxicity between chemical species.

Like many biological response tests, toxicity tests have limitations. The advantages and disadvantages of such tests are extensively summarized by Elder (1990). In general, the objective of aquatic toxicity testing is to show directly how selected organisms respond to water-borne chemicals in laboratory-controlled conditions. Specifically, in the present study, toxicity tests were made to identify which drainwater sites contained water toxic to test organisms. Freshwater and saltwater organisms were used to distinguish between the toxic effects of salinity and trace elements in whole-water (unfiltered) samples collected from selected drainwater sites in Stillwater WMA. Serial dilutions of test water also were performed to provide an estimate of the proportion of freshwater that would be required to dilute the original sample to make it nontoxic. In addition to freshwater, reconstituted water was used as a control and as dilution water. Reconstituted water is demineralized water that is made chemically similar to the actual drainwater by adding measured amounts of known salts, but without any trace-element contaminants.

The results of the three separate, but related, toxicity studies conducted in the study area during 1988-89 indicated that of the six drains that discharge directly or indirectly to Stillwater NWR, water in TJ Drain and Hunter Drain commonly was acutely toxic to both freshwater (daphnids [*Daphia magna*] and flathead minnows [*Pimephales promelas*]) and saltwater (mysid shrimp [*Mysidopsis bahia]*, sheephead minnows [*Cyprinodon variegatus*], and striped bass [*Morone saxatilis*]) organisms (Dwyer and others, 1992; Ingersoll and others, 1992; Finger and others, 1993). In addition, one or more of these studies suggested that water from Stillwater Point Diversion Drain, Lead Lake, and Pintail Bay, also exhibited a degree of toxicity to test organisms.

Depending on the source water and the kind of test organism used (freshwater or saltwater), toxicity to test organisms was due to either (1) atypical ionic composition compounded by a mixture of trace elements—specifically arsenic, boron, copper, lithium, molybdenum, and strontium; (2) atypical ionic composition of major dissolved constituents; (3) decreased water hardness; or (4) elevated salinity (Dwyer and others, 1992; Ingersoll and others, 1992). Dissolved mercury concentrations were below the analytical reporting limit of 0.3 µg/L in all source water (Finger and others, 1993).

Toxicity tests also were made on water from six USGS wells completed in the shallow aquifer (well depths less than 30 ft). The wells are located throughout a non-irrigated area, and were selected because of their proximity to drains or wetlands in or near Stillwater NWR. The results of these tests showed that water from five wells was acutely toxic to both freshwater (daphnids and fathead minnows) and saltwater (striped bass) organisms. The toxicity to freshwater organisms was likely due to salinity stress alone, whereas toxicity to salt-tolerant organisms may have been due to exposure to atypical ionic composition and mixtures of trace elements (S.A. Burch, USFWS, Columbia, Mo, written commun., 1991).

The results of the toxicity studies showed that (1) water from some drains was toxic to both freshwater and saltwater species; (2) deep drains that intercept poor-quality ground water, particularly near areas of ground-water discharge, provide a surface conduit for quickly transporting potentially toxic water to a wetland—with travel times in terms of feet per second compared to feet per year for ground-water flow; (3) frequent measurements of specific conductance with analysis of some water samples for determining the concentration of major ions and trace elements is desirable for any water-quality monitoring in the Carson Desert; and (4) the concentration of individual contaminants did not provide information on the interactive effects of contaminant mixtures and atyptical ion composition on the effective lethal concentration, thus demonstrating the value of using whole-water toxicity tests in the study area.

Environmental Pathways of Selenium and Mercury

An important consideration in evaluating the effects of known irrigation-induced water-quality problems is the tendency of certain trace elements to be biomagnified up the food chain. The consumption of selenium- and mercury-containing aquatic organisms that are eaten by fish and waterfowl, which in turn may be eaten by humans, is a principal pathway leading to toxicity (Lemly and Smith, 1987). Other trace elements, such as arsenic and boron, are toxicants at sufficiently high concentrations, but neither element is known to biomagnify to higher trophic levels.

Concentrations of dissolved selenium in most drainwater (and generally in most samples of ground water) in the study area were persistently low. These low concentrations confounded the interpretation of how selenium was transported through the abiotic-biotic system. On the other hand, selenium was biomagnified 10,000-fold in some waterfowl tissues (R.J. Hallock and others, 1993a).

A preliminary hypothesis developed during the earlier reconnaissance investigation regarding selenium and mercury transport was that the pathway is from bottom sediment to biotic targets (Hoffman and others, 1990, p. 72). For example, the apparent selenium pathway was:

bottom sediment → aquatic insects → birds.

The results of the detailed study, however, suggest that the pathway is more complex than the original hypothesis. On the basis of the work of Lico (1992) and R. J. Hallock and others (1993a), the probable principal abiotic-biotic pathway for selenium is:

unsaturated zone (source of selenium) → shallow aquifer → irrigation drains → plants in drains → wetland environment → insects [and plants] → waterfowl [and fish].

Selenium is naturally present in aquifer material and, in some places, is mobilized by downward-percolating irrigation water to mix with water in the shallow alluvial aquifer. Along the flow path, ground water containing selenium may be intercepted by the many miles of open drains that serve the agricultural area.

Mercury contamination, on the other hand, was derived principally from man-caused activities in the upstream reach of the Carson River during the mid-1800's, thus predating the Newlands Irrigation Project. Because of the affinity of mercury to sorb on particulate matter (organic and inorganic), it is commonly transported downstream during high streamflow. Because of historical flow patterns, which are confirmed by contemporary sediment data (Cooper and others, 1985; Tidball and others, 1991), most of the mercury was deposited in Carson Lake, Stillwater Marsh, the mouth of the Carson River in Carson Sink, as well as along the floodplain of the river. The vast network of canals, laterals, and drains of the Newlands Irrigation Project has widely distributed mercury-bound fluvial sediment throughout the area. In contrast to selenium, the contaminant pathway for mercury thus appears to be:

fluvial-sediment transport → bottom sediment → bottom-dwelling biota (plants; forage fish) → waterfowl.

According to R.J. Hallock and others (1993a), bioaccumulation of selenium and mercury by plants and biomagnification in insects principally occur in drains of the agricultural area. Apparently, a large inventory of selenium and mercury is fixed in aquatic biomass in irrigation drains. As a consequence of biomagnification of mercury in edible portions of certain waterfowl in 1986-87, a public-health warning was issued in 1989 by the Nevada State Health Division limiting the amount of shoveler duck tissue from Carson Lake that could be safely eaten. The human-health warning level for mercury is 1.0 µg/g, wet weight. Results of the detailed study (R.J. Hallock and others, 1993b) reconfirmed the high mercury concentrations in shoveler ducks found during the reconnaissance study (Hoffman and others, 1990). But in addition, high mercury levels were found in other duck species from both Carson Lake and Stillwater WMA.

Although selenium is biomagnified in some duck tissue, the concentrations in muscle examined in 1989 were below the human-health warning level of 2 µg/g, wet weight. Thus, the issuance of a human-health warning for selenium in edible tissue was not warranted for Carson Lake and Stillwater WMA. Other nearby wetlands were not evaluated because they were nearly dry just prior to the 1989 waterfowl season. Few, if any, ducks were available to hunters.

The results of the detailed study of contaminant pathways (R.J. Hallock and others, 1993a), point out the importance of sampling and trace-element analysis of aquatic plants, drift, and detritus in drains throughout the Fallon agricultural area. Many water-quality sampling programs for trace elements commonly include data for only the dissolved (or filtered) phase of water. By this operational exclusion, some chemical elements that are temporarily stored in plant tissue (living and detrital) are often not reported in both living and nonliving matter.

Waterfowl Production

The toxic effects of selenium and mercury on waterfowl production are expressed in two ways: (1) reproductive failure and (2) mortality of juveniles and adults. Because the Stillwater, Fernley, and Humboldt WMA's, and the wetlands of Carson Lake are managed mainly to support migratory species, principally waterfowl, the production of nesting waterfowl is an important indicator of the health of the wetland ecosystem. Accordingly, a waterfowl-production study in 1988 (L.L. Hallock and others, 1993) was done as part of the DOI detailed study. The results of that study showed that mercury, selenium, and boron concentrations in 114 duck and coot eggs, for the most part, were below levels expected to cause reproductive failure. Also, no apparent physical abnormalities of embryos or newly hatched ducklings were observed from 69 artificially incubated eggs, nor from 36 naturally incubated eggs from the study area. However, in the 124 juvenile duck and coot livers analyzed for trace-element concentrations, mercury and selenium were found in sufficiently high concentrations in some areas to be likely to have an adverse effect on waterfowl production. Mean concentrations of boron in livers of juvenile waterfowl were all below the level expected to adversely affect duckling growth. Mercury contamination is of concern in Carson Lake and Stillwater WMA, where about half of the birds collected had concentrations high enough to likely decrease production. Selenium is of concern in Fernley and Humboldt WMAs, and in Mahala and Massie Sloughs, where more than half of the juvenile birds collected had concentrations probably high enough to cause reproductive failure or, in some cases, toxicosis. These conditions existed to a lesser extent in Stillwater WMA (L.L. Hallock and others, 1993). Another environmental factor that may cause a direct or indirect decline in waterfowl production is the lack of water and attendant decrease in water quality. Therefore, the reported substantial decrease in waterfowl production from 1968 to 1988, a drought period, was attributed primarily to loss of both nesting and protective habitat owing to reductions of water discharged to the wetlands (L.L. Hallock and others, 1993).

SUMMARY AND CONCLUSIONS

A study was begun in water year 1988 to examine in detail the source, transport, and fate of potentially toxic constituents associated with irrigation drainage in and near the Stillwater Wildlife Management Area (WMA). This detailed study was an outgrowth of the U.S. Department of the Interior (DOI) 1986-87 reconnaissance investigation of water quality, bottom sediment, and biota (Hoffman and others, 1990). Both studies were funded and led by agencies within the DOI as part of the National Irrigation Water Quality Program (NIWQP).

The results of the detailed study have been published in a data report (Rowe and others, 1991) and two interpretive reports—one on hydrogeochemisty (Lico, 1992), and the other on aquatic biota (Hallock and Hallock, 1993). In addition, the results of other specific or topical investigations related directly to the detailed study reported here, and which also were funded by the NIWQP, were published in journals (Oremland and others, 1991; Dwyer and others, 1992; Ingersoll and others, 1992; Steinberg and others, 1992). The present report melds and summarizes the information presented in all related reports involving diverse technical disciplines.

To fulfill technical objectives of the detailed study, discussions on the questions posed earlier in this report are presented below:

1. *How have the Stillwater wetlands changed with respect to the quantity and quality of water since the advent of large-scale irrigation in the early 1900's?*

Documentation of wetland conditions prior to 1900 is sparse. The few available historical accounts describe an area of generally luxuriant vegetation with a diverse assemblage of wildlife, including many species of waterfowl. Explorers and explorer-scientists commonly described the water as alkaline, but generally drinkable "on the trail." The wetlands waxed and waned naturally in response to annual variations in streamflow of the Carson River, which may have averaged 410,000 acre-ft/yr. The quality of water would have varied substantially with varying flow regimes, as it does today. Before 1900, the largest wetland most of the time, in terms of sustained acreage, probably was Carson Lake. Since the beginning of large-scale irrigation in the Carson Desert in the early 1900's, the principal source of water for the wetlands was poor-quality irrigation return flows and irregular, but important, operational spills of good-quality irrigation water. Beginning in 1988, with mandated increased efficiencies of the irrigation system, the overall amount of water entering the historical wetlands at Carson Lake and Stillwater Marsh was reduced to about 60,000 acre-ft/yr, with most of the reduction consisting of relatively high-quality spilled water. The net result of reduced water delivery was about a 50-percent reduction in wetland size, and a four- to seven-fold increase in average dissolved-solids concentrations in drainwater. As a consequence, the wetland ecosystem appears to be poorer in terms of biological diversity and vitality.

2. *What areas contribute the greatest dissolved-solids and trace-element concentrations and loads to receiving wetlands?*

Hunter Drain and TJ Drain consistently had the highest concentrations of dissolved solids and potentially toxic dissolved trace elements—arsenic, boron, lithium, and molybdenum—of all drainwater entering Stillwater Marsh. Flow in the two drains, however, was often much less than flow in other drains entering Stillwater Marsh. In terms of the small acreage that both Hunter and TJ Drains serve, each contributes a substantial percentage of the trace-element and dissolved-solids loads that enter Stillwater Marsh. During the irrigation season, irrigation drainage may be the dominant component of flow, but an important year-round component of flow in some drains (TJ, Paiute Diversion, and possibly Hunter) is seepage of shallow ground water containing high concentrations of solutes. The TJ Drain system was constructed in the early 1980's to lower the local water table to support irrigated agriculture on the Fallon Indian Reservation. Hunter Drain, constructed in the 1940's, receives drainage from a few (undetermined number) acres of farm land south-southwest of Stillwater Point Reservoir. Hunter Drain was deepened in the 1950's to intercept a local rise in the water-table that resulted from an increase in the water level of Stillwater Point Reservoir. Thus, in some areas, ground-water flow to some lakes (or drains) depends on water levels of nearby lakes. Stillwater Point Diversion Drain contributed the largest load of dissolved solids (about 40 percent of total) to Stillwater NWR compared with the other five drains, and in general, the concentrations of trace elements were relatively low. Flow in Stillwater Point Diversion Drain is an unquantified mixture of irrigation drainage and treated sewage effluent.

3. *What hydrogeochemical processes are responsible for the mobilization and transport of certain potentially toxic constituents?*

As oxygenated irrigation water of low dissolved-solids content infiltrates to the shallow alluvial aquifer, it dissolves the sediment matrix and associated naturally occurring trace elements, thus increasing the concentrations of solutes in the water. Down the flow path, dissolution and desorption processes predominate under oxidized and alkaline conditions to further increase solute concentrations in ground water. These conditions are conducive to the mobilization and transport of arsenic, lithium, molybdenum, and selenium in the Carson Desert. Boron is mobile under a wide range of geochemical conditions. The reaction of water with the solid phase is facilitated by the nature of coatings on the buried fine-grained sediment particles. Still farther along the flow path, near the area of ground-water discharge, the concentrations of solutes (including trace elements) in the shallow ground water are increased even more by evapotranspiration. These processes are driven by depth to water, air temperature, wind, and abundance of plants.

4. *What processes control aqueous selenium concentrations in drains and wetlands?*

In some lakes and drains in the study area, selenium (as selenate) from the overlying water is retained in the bottom sediment by a biochemical process. This process is carried out by selenate-reducing bacteria in anaerobic environments; however, the process is apparently inhibited by dissolved nitrate. The inhibition by nitrate may partly explain the apparent ability of selenate in ground water to pass through anaerobic sediment at the bottom of drains to mix with drainflow, and thus be available for biological uptake. If so, nitrate-rich water must be treated before bacterial selenate reduction can proceed and be used as an effective bioremediation technique. Uptake by aquatic plants also removes selenium and other trace elements from the water column, albeit temporarily.

5. *What are the biological pathways of mercury and selenium?*

The detailed study of contaminant pathways indicates that mercury and selenium from irrigated fields are bioaccumulated in aquatic plant material (both living and detrital) and are biomagnified in aquatic insects in agricultural drains. At times, this biotic and abiotic material is flushed by high drainflow and transported to receiving wetlands. These inputs of mercury- and selenium-bearing material from the drains are exposure pathways to fish and waterfowl. In general, the areas of highest recorded concentrations for particulate-bound mercury were along the historical channels of the Carson River and in and near Carson Lake; and for particulate-bound selenium, the highest concentrations were along a northeast trend from the city of Fallon.

6. *For human-health concerns, what are the mercury and selenium levels in edible parts of ducks?*

As a consequence of the biomagnification of mercury in edible portions of certain waterfowl in 1986-87, a public-health warning was issued in 1989 by the State of Nevada that limited the amount of shoveler duck tissue from Carson Lake that could safely be eaten. Results of the detailed study in 1987-90 reconfirmed the high concentrations of mercury in shoveler ducks found during the reconnaissance investigation. The 1 $\mu g/g$, wet weight, human-health warning level for mercury was exceeded in 90 percent of the shoveler muscle samples, with a mean concentration exceeding the health warning six-fold, and the health warning remained in effect for Carson Lake. High mercury levels were found in duck species in addition to shovelers from both Carson Lake and Stillwater WMA. Although selenium is biomagnified in some duck tissue, the concentrations in muscle tissue examined in 1989 were below the human-health warning level of 2 µg/g, wet weight.

7. *Is some drainwater and subsurface water toxic to both freshwater and saltwater aquatic organisms? And what chemical agents are responsible for the observed acute toxicity?*

Toxicity tests showed that water samples from TJ Drain, Hunter Drain, and the shallow ground water near TJ Drain were acutely toxic to both freshwater and saltwater-tolerant test organisms. Water from other drains and wetlands exhibited a lesser degree of toxicity. Toxicity of sampled water to both freshwater and saltwater-tolerant organisms was attributed to either high salinity, decreased water hardness, or atypical ionic concentrations compounded by the combined presence of trace elements—arsenic, boron, copper, lithium, molybdenum, and strontium. Mercury concentrations in all filtered water samples used for the toxicity tests were below the analytical reporting limit of 0.3 µg/L.

8. *Are mobilized trace elements causing embryonic abnormalities or death of migratory waterfowl?*

Waterfowl hatching rates were considered normal and no embryonic abnormalities were observed. Although boron, mercury, and selenium concentrations in eggs were generally at or below adverse effect levels, livers of juvenile birds confined to wetlands exceeded effect levels for mercury and selenium, which may have adversely affected waterfowl production. Waterfowl production is greatly reduced from historical levels, but nest predation and habitat loss resulting from lack of water, rather than trace-element toxicity, are probably the main causes.

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Computer-enhanced photograph of moonrise over snowcapped Stillwater Range. Photographed by Patrick A. Glancy, 1978.

GLOSSARY OF SELECTED TERMS

Aerobic. Able to live or grow only where molecular oxygen (O_2) is present; oxic.

Abiotic. Pertaining to nonliving matter.

Adsorption. The adhesion of a substance to the surface of a solid.

Algae. Simple plants, many of which are microscopic, that contain chlorophyll. Most algae are aquatic and may become a nuisance when environmental conditions are suitable for prolific growth. Some algae produce toxins that, when ingested, kill other organisms or cause illness in humans.

Anaerobic. Able to live or grow in the absence of molecular oxygen (O_2).

Antagonism. The counteraction between two contaminants that lessens the harmful effects of one or the other.

Aquifer. Rocks or sedimentary deposits that yield usable quantities of ground water to wells and springs.

Base flow. Water entering a stream channel from ground water or other delayed source of recharge.

Bioaccumulation. The ability of an organism to accumulate a chemical to concentrations of one or more orders of magnitude greater than the concentration in water or food.

Biomagnification. The accumulation of progressively higher concentrations of a chemical by successive trophic levels of a food chain.

Biota. The plant and animal life of a region.

Biotic. Pertaining to living matter.

Bloom. A large concentrated growth or aggregation of plants, such as algal bloom.

Contaminant. An element or compound at sufficient concentrations known to have acute or chronic adverse effects on plants, animals, or humans.

Desorption. The release of a substance adhered to a solid.

Detritus. A thin layer of oxic bottom sediment near the water-sediment interface that consists of fine particulate debris, mostly organic.

Dissolution. To dissolve a substance in water.

Downgradient. In the direction of decreasing hydrostatic (water pressure) head. Loosely, "downhill."

Drainage basin. An area of the Earth's surface in which water drains into a specific stream system.

Drainage [drain] water. Surface and subsurface water from irrigated areas that may be commingled with precipitation, surface runoff, and ground-water flow from non-irrigated lands.

Drought. An indefinite period of deficient precipitation or runoff with no set standard by which to determine the duration or amount of deficiency. Thus, no quantitative definition of drought is universally accepted; generally, each investigator establishes his own definition.

Ecosystem. The interaction of a group of living organisms with their environment and the exchange of matter and energy between the abiotic and biotic environment.

Emergent aquatic plants. Plants that are rooted in the bottom sediments and project above the water surface, such as cattails and bulrushes.

Effective porosity. The ratio, usually expressed as a percentage of total volume, of the pore space of a saturated soil or rock mass that can be drained by gravity.

Evapotranspiration. The sum of the processes by which water is withdrawn from the surface of the soil or body of water by evaporation and by plant transpiration.

Ground water. Water beneath the land surface contained in interconnected pores in the saturated zone that is under hydrostatic pressure.

Hardness. The measure of the amount of alkali metal ions, principally calcium, magnesium, and iron, dissolved in water.

Invertebrates. Animals without backbones.

Irrigation return flow. Water used for irrigation purposes that is not consumed by plants but moves to a surface- or ground-water body. The flow includes tail-water runoff, percolation losses, and seepage.

Irrigation water. Water diverted from surface water or ground water to grow crops.

Isotopes. Atoms of the same element that differ in mass because of a difference in the number of neutrons in the nucleus of the element.

Lateral. Side canal.

Macrophyte. Complex plants, visible to the unaided eye, with roots and vascular system.

Median. A statistical measure of central tendency; the middle number in an array of values in ascending or descending order.

Nutrient. Any substance that is required by a living organism for the continuation of growth, tissue repair, or for reproduction; for example, nitrogen, phosphorus, and carbon.

Oxic. See **Aerobic.**

Oxidation-reduction (redox). A chemical reaction in which an atom or molecule loses electrons to another atom or molecule. Oxidation is the loss of electrons; reduction is the gain in electrons.

Permeability. The capacity of a material for transmitting a fluid.

Periphytic. Attached to a solid surface.

Potentiometric surface. An imaginary surface representing the static head of ground water and defined by the level at which water will rise in a tightly cased well.

Saline water. Water that contains more than 1,000 mg/L of dissolved solids. It is considered unsuitable for human consumption and less desirable for irrigation because of its high content of dissolved solids. Salinity generally is expressed as milligrams per liter of dissolved solids, with 35,000 mg/L defined as seawater. A general salinity scale is:

Salinity category	Dissolved solids (milligrams per liter)
Fresh	0 to 1,000
Slightly saline	1,000 to 3,000
Moderately saline	3,000 to 10,000
Very saline	10,000 to 35,000
Briny (brackish)	Greater than 35,000

Saturated zone. The zone below the water table in which all pore spaces are filled with ground water.

Seepage. Movement of water in saturated material (for example, ground water discharging into drains).

Spills (operational spills). Intentional releases of water from an irrigation water delivery system (reservoir, wasteways, canals) in excess of needs to meet irrigation demand.

Soluble. Capable of being mobilized in solution. At times used interchangeably with the term "dissolved."

Solute. A substance present in solution.

Static head. The height above a standard datum of the surface of a column of water (or other liquid) that can be supported by the static pressure at a given point. The static head is the sum of the elevation head and the pressure head.

Submergent aquatic plant. A plant that grows beneath the surface of water, except when flowering, such as pondweed and coontail.

Sump or Sink. Any low area that receives drainage water.

Synergism. The action of two or more substances, organs, or organisms to achieve an effect of which each is individually incapable. For contaminants, the combined action is usually harmful.

Tail-water runoff. Irrigation water that runs off the surface of irrigated fields.

Toxicity. The capacity of a material to produce injury, disease, or death upon exposure, ingestion, inhalation, or assimilation by a living organism.

Trace element. Any element present in minute concentrations, usually expressed in terms of micrograms per liter when present in water.

Transpiration. The process by which plants take up water and release it as vapor through their leaves.

Trophic level. A stage in the food chain of an ecosystem.

Unsaturated zone. The zone between the land surface and the water table. It includes the root zone, intermediate zone, and capillary fringe.

Upgradient. In the direction of increasing static head. Loosely, "uphill."

Water table. The upper surface of the saturated zone.

Water year. 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."

Wetland. Land that is sometimes or always covered by shallow water or has saturated soils most of the time, and where plants adapted for life in wet conditions usually grow.

Void. Space in a soil or rock mass not occupied by solid matter; also known as pore space.

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