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

Part A. Water Quality, Sediment Composition, and Hydrogeochemical Processes in Stillwater and Fernley Wildlife Management Areas

By Michael S. Lico

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Conversion Factors

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

For 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 both the United States and Canada.

Abbreviated Water-Quality Units Used in This Report

- µg/L (microgram per liter)
- µm (micrometer)
- µS/cm (microsiemen per centimeter at 25°C)
- mg/kg (milligram per kilogram)
- mg/L (milligram per liter)
- mm (millimeter)
- mmol/L (millimole per liter)
- mol/L (mole per liter)
- mV (millivolt)

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ABSTRACT

A water-quality reconnaissance study 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). This study prompted the U.S. Department of the Interior to initiate a more detailed study to determine the geochemical and physical processes that control water quality in the Stillwater WMA. The Lead Lake area in Stillwater WMA was studied in detail to determine these processes. Water samples were collected from agricultural drains and canals that carry a mixture of irrigation-return flow and ground-water seepage. The hydrologic characteristics of both the surface and shallow ground water in Stillwater WMA are complex; the water quality of Fernley WMA also was studied because of the area's relatively simple hydrology. The understanding of hydrogeochemical processes in the Fernley WMA were then applied to a definition of the processes active at Stillwater WMA.

Water in Stillwater WMA is of poor quality and, during the recent drought conditions from 1986 to 1990, is substantially reduced in quantity. Constituents of concern that exceeded Federal or State criteria for the protection of aquatic life in surface water are arsenic, boron, and mercury. Dissolved solids and un-ionized ammonia also are present at concentrations that exceed criteria for the protection of aquatic life. Ground water is an important contributor of water to the drains and to Lead Lake, and is the major component of base flow in some of the drains. The quality of the ground water in Stillwater WMA also is poor; nearly all samples exceeded Federal or State criteria for arsenic, boron, sodium, and dissolved solids. Uranium concentrations generally are high and exceeded proposed U.S. Environmental Protection Agency criteria for drinking water in many samples. In Fernley WMA, drain water commonly exceeded criteria for arsenic and boron. Water samples from lakes in Fernley WMA commonly exceeded criteria for arsenic, boron, sodium, dissolved solids, and un-ionized ammonia.

Sediment in the drains and lakes of Stillwater and Fernley WMA's is accumulating trace elements from the overlying water column. The trace elements are either incorporated into or adsorbed onto labile coatings on grain surfaces or adsorbed onto clay minerals in the sediment. Arsenic, boron, mercury, lithium, molybdenum, selenium, and uranium are enriched in drain- and lake-bottom sediments as compared with soil samples from the Carson River basin.

Processes controlling the composition of ground water at Stillwater and Fernley WMA's include evapotranspiration; dissolution of sedimentary organic matter, calcite, silicates, and possibly iron and manganese oxides; and precipitation of montmorillonite, calcite, and gypsum. Trace-element concentrations are controlled by localized redox conditions in the sediment, evapotranspiration, and interaction with organic matter and surface coatings of iron and manganese oxides on mineral grains.

Surface-water composition is controlled by the inflowing ground water, evapotranspiration, interaction with highly reducing bottom sediment, and precipitation of calcite. Precipitation of iron (oxy) hydroxide removes iron, and probably many trace elements, from the water in South Pond at Fernley Wildlife Management Area.

Stillwater Point Diversion Drain, Stillwater Slough, and TJ Drain contribute the largest part of the dissolved-solids load to Stillwater WMA (41, 23, and 19 percent, respectively, during 1988-89). TJ Drain also delivers the largest load of dissolved solids, boron, and sodium to Lead Lake.

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's) throughout the western United States have shown elevated concentrations of selenium and other trace elements that are a potential threat to the biota within the management areas (Knapton and others, 1988; Peterson and others, 1988; Radtke and others, 1988; Stephens and others, 1988; Wells and others, 1988; and Hoffman and others, 1990). In 1988, the U.S. Department of the Interior directed the Geological Survey, Fish and Wildlife Service, Bureau of Reclamation, and the Bureau of Indian Affairs to implement detailed studies that would provide the necessary information for mitigating the negative impacts of the irrigation-drainage water. The detailed studies were to provide information on the toxic constituents, their effects on biota, and a summary of significant findings.

The Stillwater WMA in west-central Nevada is one of several sites in the western United States selected for detailed examination of the mobilization, transport, and the biologic pathways of potentially toxic constituents found in the biota.

Lead Lake within the Stillwater WMA was chosen as a primary site for this study because of anomalously high numbers of bird and fish deaths in the past several years. Elements are present at potentially toxic concentrations in the water, bottom sediment, and biologic samples from Lead Lake, according to Hoffman and others (1990).

The nearby Fernley WMA was included as part of the current study because it has many similarities to the Stillwater WMA, such as climate, geologic history, depositional environments, and sediment sources, but is much less complex hydrologically. High concentrations of potentially toxic trace constituents also were present in water and biota in the Fernley WMA (Hoffman and others, 1990).

Purpose and Scope

The purpose of this report is to describe the occurrence, distribution, and processes responsible for mobilization and transport of potentially toxic constituents to Lead Lake in the Stillwater WMA, and to the wetlands in the Fernley WMA.

This report includes physical and chemical data from 15 surface-water and 25 ground-water sites in and near the Stillwater and Fernley WMA's. In addition, information on soil, Pleistocene lake sediment, and lake and drain bottom sediment are included. Data for this study were collected during 1987-89.

Description of Study Area

The Stillwater WMA is in the Carson Desert hydrographic area (Rush, 1968, pl. 1) in the western Great Basin, approximately 60 mi east of Reno in western Nevada (fig. 1). The Carson Desert, about 2,000 mi^2 in area, is a broad, alluvial basin surrounded by mountains that rise from the valley floor to altitudes as high as 8,790 ft above sea level in the Stillwater Range to the east. The valley floor (altitudes near 4,000 ft) is mostly flat and the northern part is a playa, the Carson Sink, which is approximately 400 mi^2 in areal extent. The Carson Sink is the terminus for the Carson River and, in extremely wet years, for the Humboldt River.

Stillwater WMA was established in 1948 by cooperative agreement with the U.S. Fish and Wildlife Service, the Nevada Department of Wildlife, and the Truckee-Carson Irrigation District. The agreement called for approximately 224,000 acres of the Newlands Project area to be developed and managed as Stillwater WMA, with about 24,000 acres of that area to be reserved as the Stillwater National Wildlife Refuge for administration as a nonhunting sanctuary. In July 1990, the Refuge boundaries were extended to include almost half of the Wildlife Management Area (fig. 2). Some privately owned land, including the Canvasback Gun Club, is within the Refuge area, on the western edge.

The Fernley WMA (fig. 1) is about 30 mi east of Reno and 30 mi west of Stillwater WMA, within the Fernley hydrographic area (Rush, 1968, pl. 1) which includes the town of Fernley, wetlands, and a playa--the Fernley Sink. The sink is an ephemeral lake and is the terminus for southwestward drainage from the Bradys Hot Springs and Fireball Valley areas as well as drainage from the Fernley area to the south (Van Denburgh and Arteaga, 1985). The area is relatively flat and is bounded on the south by the Virginia Range, on the west by the Truckee Range, and on the east by the Hot Springs Mountains. Altitudes range from near 4,000 ft on the valley floor to more than 7,100 ft in the Truckee Range.

The study area has cold winters and hot summers and is classified as a midlatitude desert. Average temperatures during the period 1941-1970 ranged from a minimum of 17.4°F in January to a high of 92.5°F in July for the Fallon area and 19.7°F and 94.6°F, respectively, for the Fernley area (Dollarhide, 1975, p. 3). Annual precipitation for the same period averaged 5.2 in. for Fallon and 5.4 in. for the Fernley area. Reported values for annual evapotranspiration in the Fallon-Stillwater area range from 36 in. (Pennington, 1980, p. 58-61) to about 60 in. (U.S. Bureau of Reclamation, 1987a, p. 2-24). Morgan (1982, p. 33-37) reported the average annual evapotranspiration from lakes and wetlands in the Stillwater area as about 54 in. Annual evapotranspiration rates for alfalfa croplands in the Fernley area have been reported to be between 38 and 54 in. (Pennington, 1980, p. 54-57).

Acknowledgments

The author gratefully acknowledges the assistance of the following individuals in the data-collection activities at Stillwater and Fernley Wildlife Management Areas: Ronald M. Anglin, Timothy D. Bowman, and C. Anne "Myke" Janik of the U.S. Fish and Wildlife Service; David L. Berger, Robert E. Bostic, Jennifer L. Hughes, Timothy G. Rowe, and Thomas B. Tucker of the U.S. Geological Survey; George Nelson of Fernley for permission to sample his well; and Allen Galloway of Fernley who graciously allowed sampling wells to be drilled on his property.

Previous Studies

Stillwater Wildlife Management Area

A previous water-quality investigation of the Stillwater WMA is described by Hoffman and others (1990). Studies of the surface-water quality within the Carson Desert are described in reports by Rollins (1965), Van Denburgh (1973), Glancy and Katzer (1975), Cooper and others (1985), Garcia and Carman (1986), Glancy (1986), and the U.S. Bureau of Reclamation (1987a).

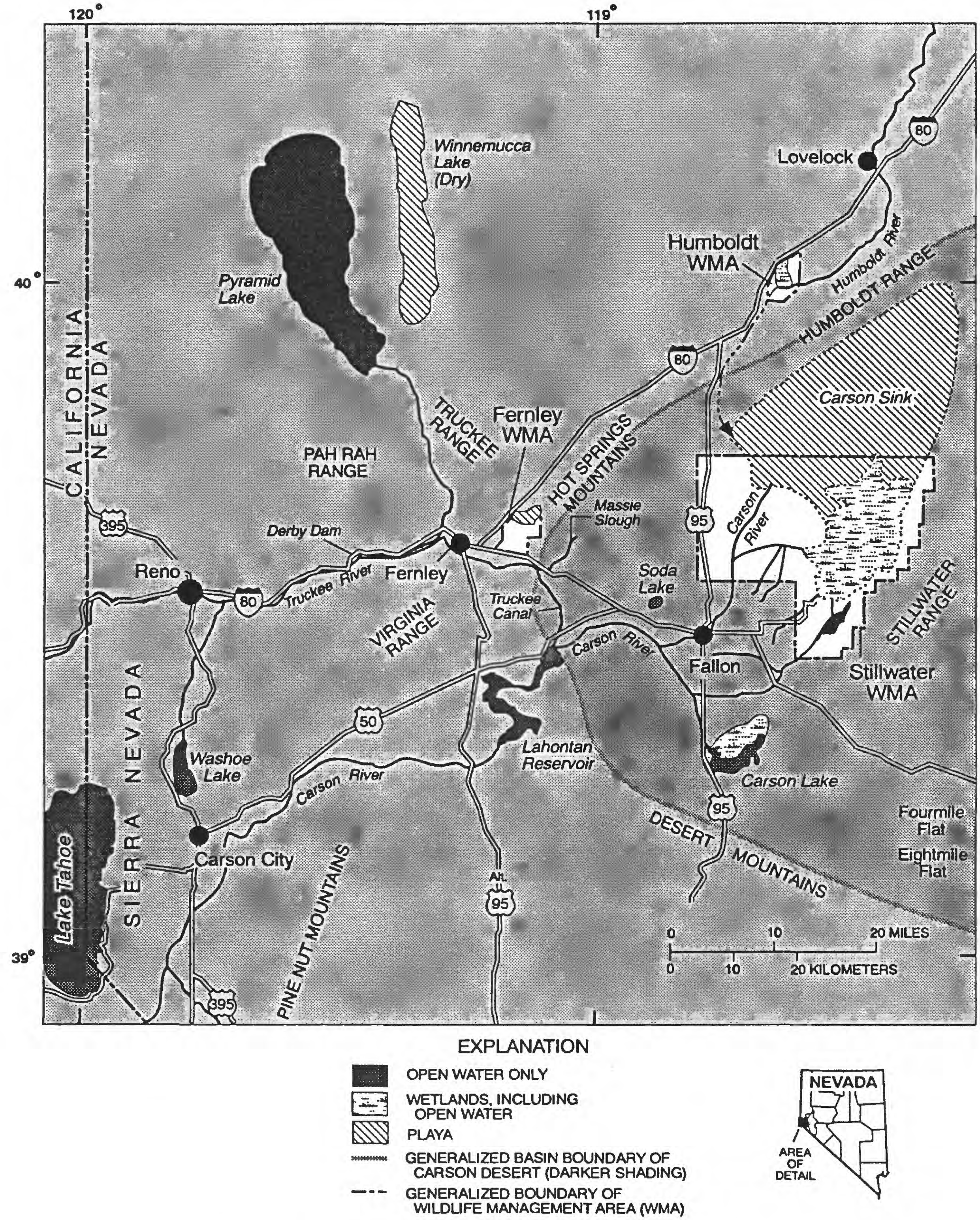

FIGURE 1. --General physiographic features in the study area and western Nevada.

Ground-water studies of the Carson Desert area are documented in reports by Stabler (1904), Glancy and Katzer (1975), Olmsted (1985), Glancy (1986), Lico and others (1987), U.S. Bureau of Reclamation (1987b), Welch and others (1989), and Hoffman and others (1990). Water quality and characteristics of geothermal systems in the Carson Desert have been reported by Olmsted and others (1975), Morgan (1982), and Olmsted and others (1984).

The geology of the Carson Desert has been described by Morrison (1964) and Willden and Speed (1974). Characteristics of soils and subsurface sediments within the Carson Desert have been reported by Strahorn and Van Duyne (1911), Dollarhide (1975), Lico and others (1986), Severson and others (1987), Harms and others (1990), and Rowe and others (1991).

Fernley Wildlife Management Area

Documentation of water quality near the Fernley WMA is sparse. An investigation by Sinclair and Loeltz (1963) described the quality of ground water in the Fernley-Wadsworth area and also of a few surface-water samples. A water budget of the Fernley basin was developed in a study by Van Denburgh and Arteaga (1985). Garcia and Carman (1986) described water quality and flows of the Truckee Canal. Brown and others (1986) described characteristics of the Truckee and Carson River systems. The geology of the Fernley area has been described by Bonham (1969), Moore (1969), Rose (1969), and Willden and Speed (1974). The soils of the Fernley basin have been mapped by Dollarhide (1975). A brief survey of soil chemistry was reported by Tidball and others (1990).

Methods Used in this Study

Sampling Wells and Piezometers

Sampling wells and emplacement holes for piezometers in the Stillwater and Fernley areas were drilled with either a 7-in.-diameter, hollow-stem auger; a 3-in.-diameter, solid-stem auger; or a 3-in.-diameter, hand-operated bucket auger. No drilling fluids were used. Each change in lithology was logged during drilling, and the logs for these wells were reported by Rowe and others (1991). Sampling wells were cased with 2-in. inside-diameter pipes made of polyvinyl chloride (PVC). Perforations were 5-ft intervals of premanufactured, machine-slit PVC well screens (0.02-in. slots). Washed Monterey sand (16-mesh) was added to the annulus to cover the screened interval; then granular bentonite was added to create a seal at least 1 ft thick. The remainder of the annular space was filled with native material excavated during drilling. A surface seal was formed by adding granular bentonite to the upper 1 ft of the annular space. The sampling wells were then developed using a surge block and by subsequently removing at least 10 well-bore volumes of water. The piezometers were constructed in the same manner as the sampling wells except that 1-in. inside-diameter PVC pipe with hand-sawn slots (approximately 0.03 in. wide) was used for casing.

The altitudes of all wells and piezometers were measured and surveyed to benchmarks. Water levels were periodically measured with a steel tape during the study.

Sediment Samples

Sediment samples for inorganic chemical analysis were collected during drilling of the sampling wells. Cores were taken through the hollow-stem auger with a stainless-steel, split-spoon drive sampler fitted with a polycarbonate liner. The cores were removed from the sampler, capped, sealed, and refrigerated until chemical analysis. Bulk sediment samples were collected from other sampling wells either as auger returns or discrete samples from the bucket auger. These samples were placed in plastic Ziploc bags and sealed.

Sediment samples from lake, drain, and canal bottoms were collected with a wide-mouth glass jar, placed into plastic containers, and sealed. At each site, the bottom sediment was sampled to a depth of about 6 in. In drains and canals, several equally spaced sediment samples were taken along a cross section of the channel. In lakes and ponds, 10 to 15 randomly spaced samples were collected and composited from within a 400-ft^2 area.

Surficial soil samples were collected at a depth of 0-12 in. using a stainless-steel shovel (R.R. Tidball, U.S. Geological Survey, oral commun., 1990).

Sediment samples for total chemical analysis were air dried, mechanically disaggregated, and sieved at the size division of 2 mm. A subsample of this sediment was sieved at 62.5 µm. Prior to analysis, the fine fraction (less than 62.5 µm) and a subsample of the less-than-2-mm fraction were digested with a mixture of hydrochloric, hydrofluoric, and perchloric acids and *aqua regia*, essentially dissolving the entire sample. Laboratory determinations of arsenic, mercury, and selenium were made by atomic-absorption spectroscopy; uranium and thorium determinations by neutron-activation analysis; and all other determinations, except for boron, by inductively coupled plasma analysis. Boron was extracted from the sediment using a hot-water extraction method (Severson and others, 1987, p. 3-4).

Total-recoverable analyses of bottom material and Pleistocene lake sediment were made using the methods outlined by Skougstad and others (1979) in which organic matter in the sediment is destroyed with hydrogen peroxide, then the sediment is extracted with a hot hydrochloric acid solution. The resulting solution was analyzed for specified trace elements by atomic-absorption spectroscopy or, in the case of boron, a colorimetric procedure.

Qualitative mineralogy of the sediment was determined using X-ray diffraction analysis. The samples were split into two size fractions (greater than 2 mm and less than 2 mm) by centrifugation. The two size fractions were analyzed using methods described by Carroll (1970, p. 51-61) and Nuffield (1966, p. 130-137). Mineralogy and digenetic changes were identified with a petrographic microscope and thin sections prepared from portions of the Pleistocene lake sediment samples. Minerals identified by X-ray diffraction and optical petrography are listed by Rowe and others (1991).

Water-Quality Samples

Surface-water samples were collected from drains, canals, and lakes according to procedures of the U.S. Geological Survey (1977, chapters 1 and 5). Onsite measurements included pH, water temperature, specific conductance, dissolved oxygen, alkalinity, and--at drains and canals--streamflow.

Ground-water samples were collected using either a peristaltic pump, air-displacement bladder pump, or an existing pump in domestic wells. Methods of sampling and field analysis for ground-water samples were those used in a previous study (Lico and others, 1987, p. 92). Onsite measurements included pH, water temperature, specific conductance, dissolved oxygen, alkalinity, and electrochemical potential (Eh). These measurements, except for alkalinity, were carried out in a flow-through cell.

Most constituents in surface- and ground-water samples were analyzed by the National Water Quality Laboratory of the U.S. Geological Survey in Arvada, Colo. Uranium and the stable isotope ratios of carbon and sulfur were analyzed by a contractor to the laboratory and stable isotopes of water were analyzed by the U.S. Geological Survey laboratory in Menlo Park, Calif. Methods of analysis used by the laboratories are described by Fishman and Friedman (1985).

In addition to the normally stringent quality-assurance practices of the U.S. Geological Survey for chemical analysis of water (Friedman and Erdmann, 1982), field blanks were processed for trace-element analysis during most sampling rounds. A field blank is a volume of deionized water that is treated as a sample in all respects, including exposure to the same water-sample containers (collecting bottle and churn splitter), filtration apparatus, chemical preservatives, and holding times, and it undergoes the same laboratory processing. The field-blank data, listed by Rowe and others (1991), show that nearly all determinations were at or below analytical reporting limits. Overall, the field-blank data indicated that inadvertent, gross trace-element contamination of water samples was either nonexistent or insignificant from a toxicity standpoint.

GEOLOGIC SETTING

Post-Mesozoic Geologic History of the Study Area

The geologic history of the Carson Desert and the Fernley basin, and the sedimentary and volcanic deposits in these basins, are similar. During Tertiary time, volcanism dominated the study area. Predominant rock types include dacite, basalt, and rhyolite. This part of Nevada was a low-lying area that drained to the sea. Lake sediments were deposited throughout the lowlands. Volcanic rocks generally were more mafic (lower SiO_2 percentage) later in the Tertiary period, with olivine basalt and andesite predominating.

During late Tertiary and early Pleistocene time, a major period of uplift and block faulting created new highlands and basins that defined the present-day topography. Closed basins (no outlet) developed at this time. Fan gravel and colluvium were deposited, and volcanic activity continued, resulting in basalt deposits near Fallon.

Lake Lahontan was the dominant geographic feature during late Pleistocene time. During its highest stand, this pluvial lake inundated more than 8,000 mi^2 (Morrison, 1964, p. 99). In the Carson Desert, more than 300 ft of lake sediments, including fine-grained deep-lake sediment, deltaic sediment, and shoreline gravel and sand were deposited during two major deep-lake cycles. These deposits are 200-250 ft thick in the Fernley area and represent four major periods of high lake level (Sinclair and Loeltz, 1963, p. AA5-AA6). Subsequently, higher temperatures and greater aridity led to the recession of Lake Lahontan and a period of eolian deposition and erosion in the Carson Desert, followed by a period of at least five cycles of lakes and subsequent desiccation, according to Morrison (1964).

Generalized Geology of the Carson Desert

The Stillwater WMA lies within the Carson Desert in the Basin and Range physiographic province. The Carson Desert is surrounded by mountains composed of a variety of igneous, sedimentary, and metamorphic rocks ranging in age from Triassic to Quaternary. The basin itself is underlain, in descending order, by (1) Holocene post-Lake Lahontan interbedded fluvial and eolian sediments, (2) Pleistocene sediment of Lake Lahontan, (3) sedimentary and volcanic rocks of Quaternary and Tertiary age, and (4) pre-Tertiary igneous and sedimentary rocks. These basin deposits exceed 8,000 ft in thickness in the Carson Desert (Glancy, 1986, p. 36). More detailed descriptions on the stratigraphy and geology of the Carson Desert are given by Morrison (1964) and Willden and Speed (1974).

Generalized Geology of the Fernley Area

The Fernley WMA lies within the central part of the Fernley basin in the western Basin and Range physiographic province. The Fernley basin is surrounded by mountains mostly composed of Tertiary to Quaternary extrusive igneous rocks. These rocks range from basaltic to rhyolitic in composition. The basin itself contains sedimentary deposits ranging in age from Tertiary to Holocene (Sinclair and Loeltz, 1963, p. AA6-AA7). These deposits, in descending order, are (1) eolian and alluvial deposits of Holocene age, (2) lacustrine deposits of Pleistocene Lake Lahontan, (3) pre-Lake Lahontan lacustrine and fluvial sediments of Pleistocene and possibly late Tertiary age, and (4) Tertiary volcanic rocks. The thickness of the basin-fill deposits is unknown, but is at least 1,026 ft (Sinclair and Loeltz, 1963, p. AA5).

HYDROLOGIC SETTING

Regional Hydrology

The hydrology of west-central Nevada, which includes the study area (fig. 1), is dominated by the Sierra Nevada range of western Nevada and eastern California. The range receives large amounts of precipitation, primarily as winter snowfall, creating a rain shadow along the eastern slopes and within the study area. The winter snowfall in the Sierra Nevada is the major source of water that feeds the Carson and Truckee Rivers, both of which flow eastward to the study area. The Humboldt River receives its runoff from snowfall in several large mountain masses in northern Nevada and flows westward to the study area. As is characteristic of the Great Basin, all three rivers within the study area are in closed basins. The Carson and Humboldt Rivers terminate in the Carson and Humboldt Sinks, respectively, and the Truckee River terminates in Pyramid Lake, a remnant of ancient Lake Lahontan.

Local Hydrology

Large-scale irrigation began in the Carson Desert and Fernley basin during the early 1900's with completion of the Newlands (Irrigation) Project by the U.S. Bureau of Reclamation. Since that time, the ground-water table has risen as much as 60 ft in the Soda Lake area (fig. 1), which is part of the Carson Desert (Rush, 1972). For a description of the Newlands Project, see Hoffman and others (1990, p. 8-13).

The hydrology of the Stillwater WMA is complex. Surface water is delivered to the area by several surface drains that carry highly variable quantities of flow from the agricultural areas surrounding Fallon. Occasionally, in very wet years such as the early 1980's, the Carson River flows reach the Carson Sink and Carson Lake. Typically, flows in the Carson River are controlled by releases from Lahontan Reservoir by the Truckee-Carson Irrigation District and the U.S. Bureau of Reclamation, in response to irrigation needs in the Fallon area. Six channels enter Stillwater WMA: Stillwater Point Diversion Drain, Stillwater Slough, TJ Drain, Hunter Drain, Paiute Diversion Drain, and D-Line Canal (fig. 2). Each of these channels carries drainage water from different parts of the Fallon agricultural area. A set of drains also serves the southern part of the Carson Desert and flows into the Carson Lake area south of Fallon. Hoffman and others (1990, p. 5-13) describe the drainage system in more detail.

Ground-water flow within the shallow alluvial aquifer system (less than 50 ft deep) of the Carson Desert area is generally northeastward and southeastward (Olmsted and others, 1984; Olmsted, 1985; Glancy, 1986), and discharges in the Carson Sink or Fourmile Flat and Eightmile Flat areas, respectively (fig. 1). Locally, ground-water flow directions and magnitudes in the shallow alluvial aquifer are highly variable. Flow is dependent on irrigation practices and locations of drains and canals relative to each irrigated field. An example of such a field, described in another report, is in the southern Carson Desert where the predominant flow direction was to the west (Lico and others, 1987, p. 93-95).

Within the borders of the Stillwater WMA, ground-water flow directions are highly variable. Flow directions and magnitudes are dependent on water-level altitudes in adjacent shallow lakes, drains, and canals. Most of the lakes, drains, and canals in the Stillwater WMA recharge the shallow alluvial aquifer. One exception to this is Lead Lake; it receives substantial inflow from shallow ground water, as indicated by the gradient of the water table near the south end of the lake. Lead Lake is the deepest lake (10 to 15 ft deep) in the management area; thus it may have greater interaction with the shallow ground water than other wetland units in the area. Water-table altitudes of the shallow aquifer around Lead Lake in April 1989 are shown in figure 3. Between 1987 and 1989 the water-level altitude of Lead Lake changed as much as 2.5 ft (fig. 4)

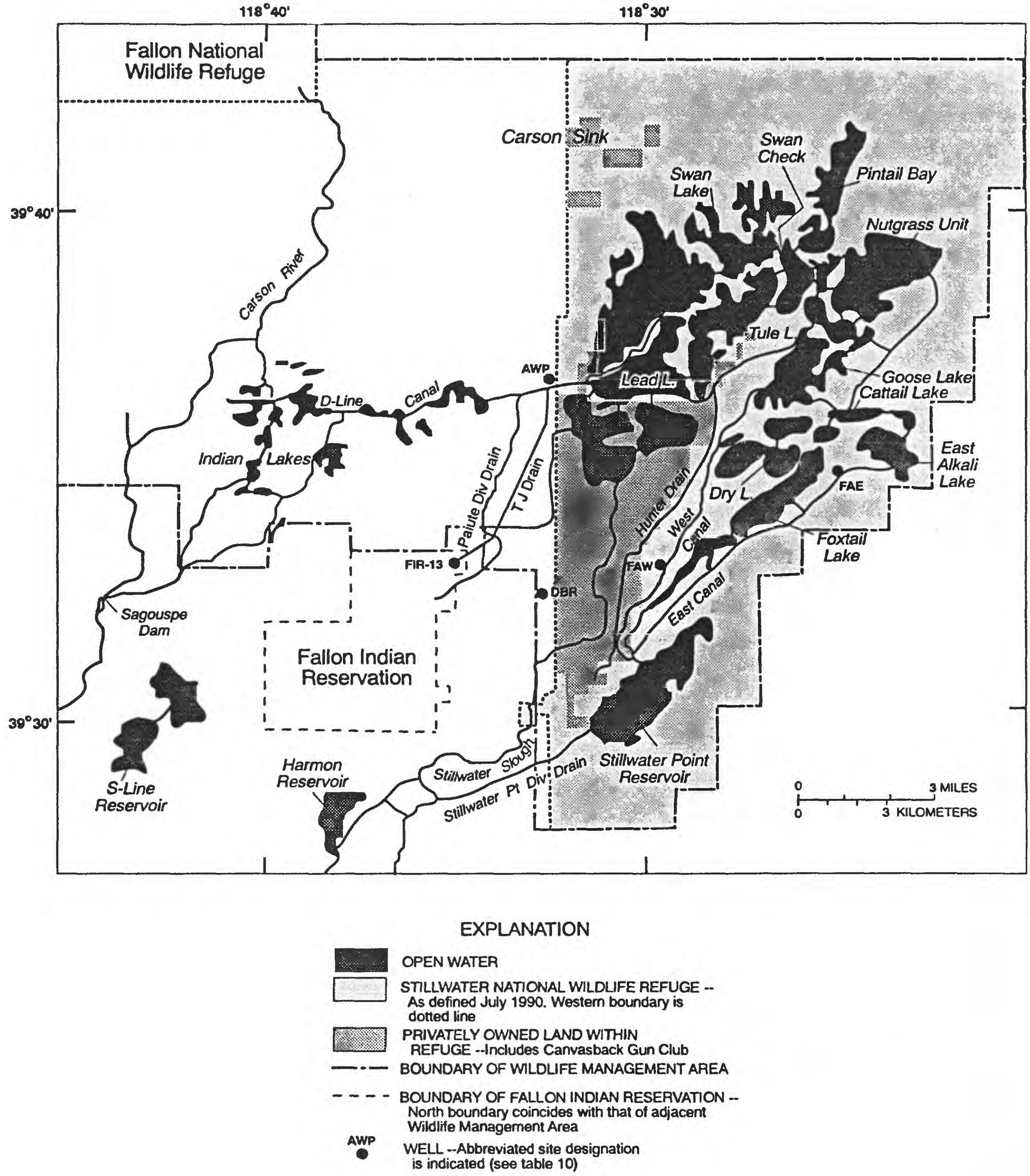

FIGURE 2. --Location of study sites and important hydrologic features in and near Stillwater Wildlife Management Area. Modified from U.S. Department of the Interior (1988, Appendix E)

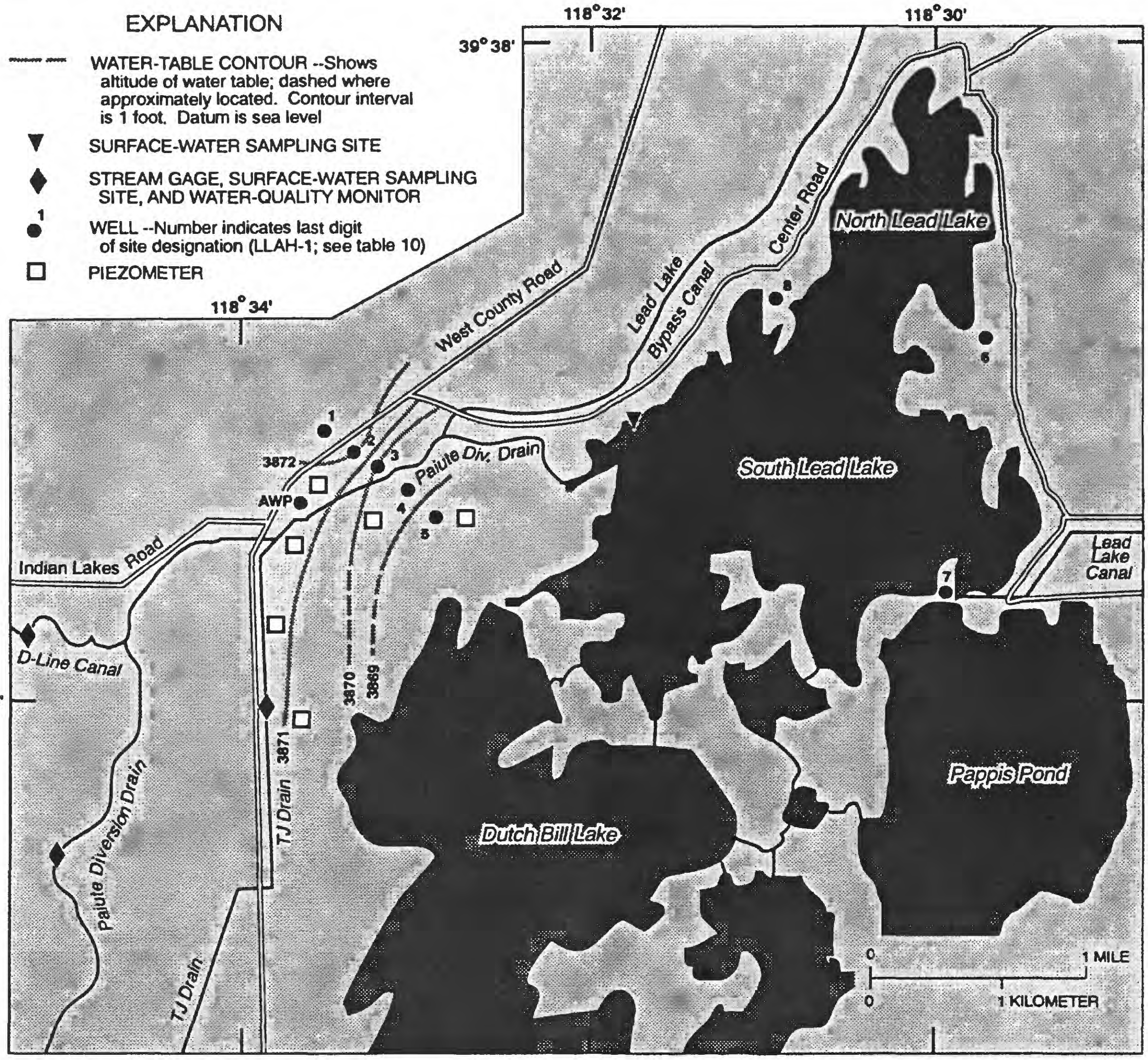

FIGURE 3. --Location of sampling sites and piezometers near Lead Lake in Stillwater Wildlife Management Area, and water-table contours for April 1989.

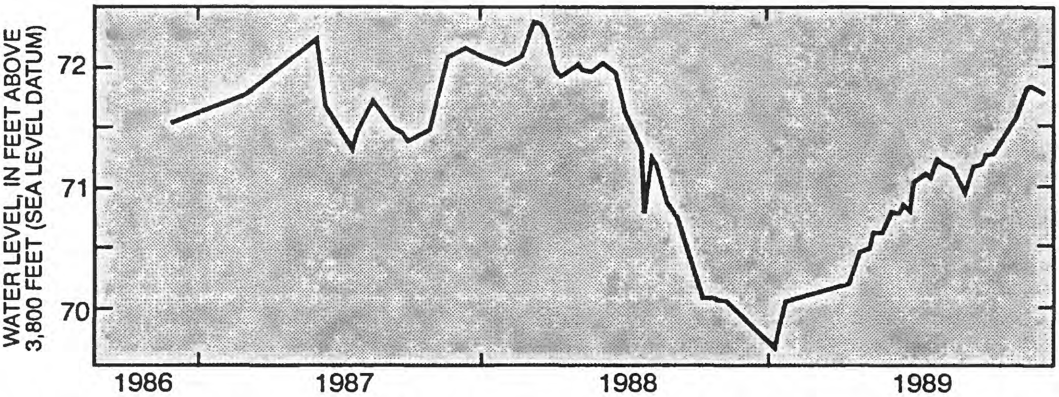

FIGURE 4. --Water-level altitudes of Lead Lake in Stillwater Wildlife Management Area,1986-89 (U.S. Fish and Wildlife Service, unpublished data, 1990).

The Fernley WMA (fig. 5) receives inflow from both surface- and ground-water sources. Essentially all surface water entering the Fernley basin is from the Truckee River by way of the Truckee Canal. This water is used for irrigation (about 26,000 acre-ft in an average year) in the Fernley area, primarily to grow alfalfa and pasture.

A network of surface drains (fig. 5) removes water from the shallow subsurface of the Fernley agricultural area. These drains also receive some surface runoff of excess irrigation water and runoff during storms. Three major drains--the Fernley, Streiff, and A-drains--coalesce to flow into the Fernley WMA (fig. 5). A small quantity of water flows into the Fernley WMA from a hot spring in the southeastern part of the area.

The Fernley WMA, managed by the State of Nevada Department of Wildlife, consists of a series of shallow (about 5 ft deep) ponds. These ponds are arranged in a "flow-through" system where each succeeding pond receives water from the "upstream" pond. Dissolved-solids concentrations increase along the flow path, and the water eventually is released to the Fernley Sink when it is too saline to support most wildlife in the management area.

Ground water in the Fernley basin is recharged by seepage from the Truckee Canal and infiltration of Truckee Canal water diverted and used for irrigation. Estimates of average canal seepage and diversions for irrigation are given by Van Denburgh and Arteaga (1985, p. 9) as 24,000 and 26,000 acre-ft/yr, respectively. Precipitation is a minor component (about 1 percent of annual recharge) of the budget (Van Denburgh and Arteaga, 1985, p. 6). In and near the Fernley WMA, ground water generally flows northward toward the Fernley Sink. Figure 5 shows the altitude of the water table in June 1989. As can be seen in figures 5 and 6, ground water flows northward or northeastward in the southern part of the Fernley basin, which indicates that the Truckee Canal is a source of recharge to the shallow aquifer along its entire length.

In the southern part of the Fernley basin, ground water discharges along a line of seeps at the base of the prominent break in topography. At this point the water moves toward the agricultural drains, adding to their flow. Ground water also discharges along A-drain and in a large area to the south of South Pond (fig. 5), where it directly enters the Fernley WMA at the southern end.

Ground water also enters the Fernley WMA from discharging springs and seeps along the base of the Truckee Range west of the management area. This water flows primarily to the Fernley Sink, thus not directly affecting the main ponds of the Fernley WMA. No ground water seeps directly to the ponds due to a slight downward gradient; however, an upward gradient exists on the playa (Fernley Sink) as indicated by the presence of flowing wells.

Geothermal fluids may influence the ground-water system near the southeastern part of the Fernley WMA where a strong upward gradient exists, but the extent of this influence is unknown.

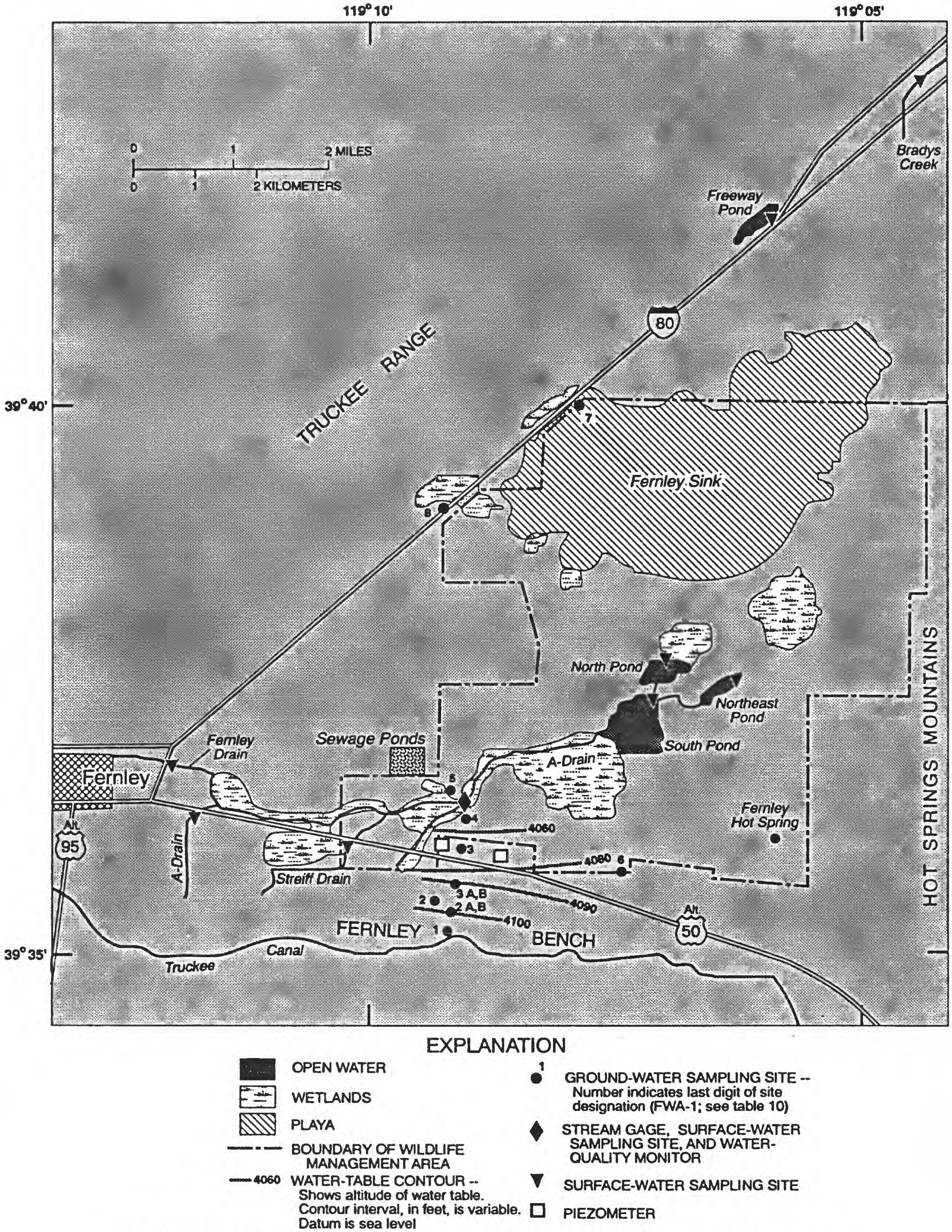

FIGURE 5. --Location of sampling sites and piezometers in and near Fernley Wildlife Management Area, and water-table contours for June 1989.

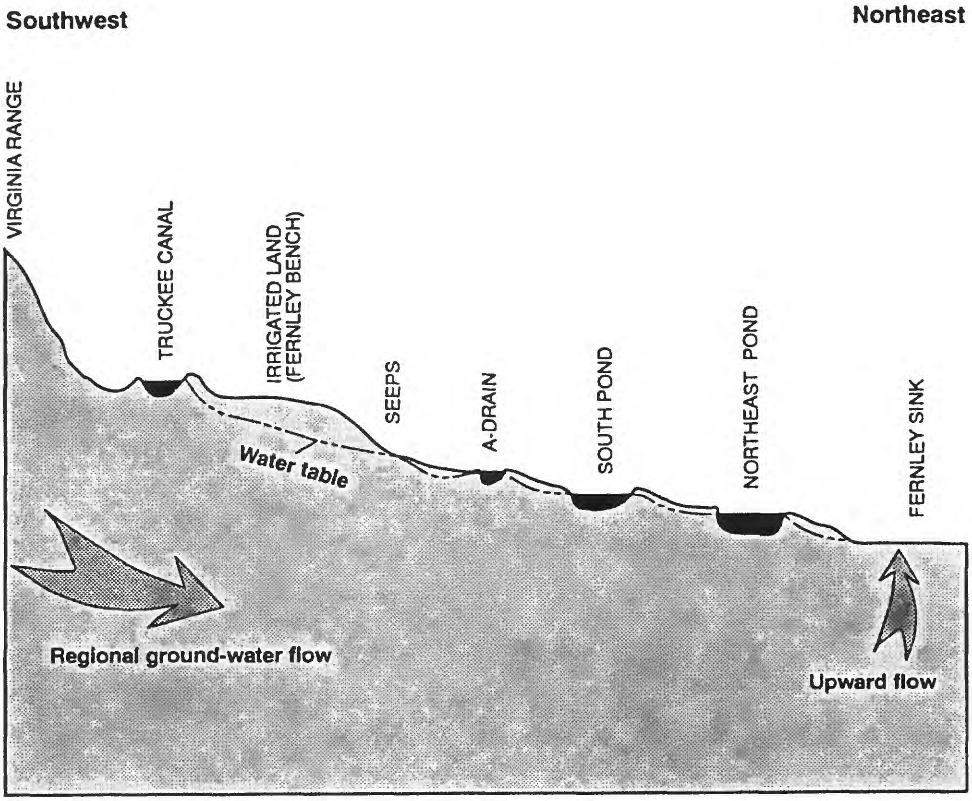

FIGURE 6. --Schematic cross section showing relation of hydrologic features to topography in the southern part of the Fernley basin. Diagram is not to scale.

WATER QUALITY

Water-quality samples collected in this study, and described below, were "instantaneous samples" and, as such, represent the quality of water at the time of sampling. However, water quality can change considerably during short time intervals; therefore, instantaneous values should not be taken as representative of "average" water quality. Continuous measurements of pH, specific conductance, dissolved oxygen, and water temperature in drains entering Lead Lake indicate this variability. The fluctuations in specific conductance are shown in figure 7. All continuous and instantaneous water-quality data were documented by Rowe and others (1991). The following description of water quality in surface and ground water uses the terminology "dilute," "briny," and so forth for dissolved-solids concentrations (Hem, 1985, p. 157). Water types (for example, sodium-bicarbonate) were ascribed on the basis of the relative concentrations of ions, in equivalents per liter, as described by Back (1961).

The terms "constituents of concern" and "criteria" are used in this report as follows: constituents of concern are elements or compounds identified by Hoffman and others (1990) as being present in concentrations that could pose a threat to wildlife or human health; criteria are beneficial-use criteria that are either State or Federal criteria or levels that have been shown to adversely affect wildlife (Hoffman and others, 1990); these are listed in table 1.

TABLE 1.--*Statistical summary of dissolved constituents of concern (Hoffman and others, 1990) in surface-water samples from sites in and near Stillwater Wildlife Management Area, 1987-89. For each three-line data group, upper number (in parentheses) is median concentration, middle numbers are minimum and maximum concentrations, and lower numbers (in parentheses) are number of samples exceeding criteria per number of samples analyzed*

[Abbreviations and symbols: mg/L, milligrams per liter; N, nitrogen; NC, median value was not calculated because more than 50 percent of the concentrations were below analytical reporting level; µg/L, micrograms per liter; SWMA, Stillwater Wildlife Management Area; <, less than]

Sites	Un-ionized ammonia (mg/L as N)[1]	Arsenic (µg/L)	Boron (µg/L)	Selenium (µg/L)	Sodium (mg/L)	Dissolved solids (mg/L)	Uranium (µg/L)
Beneficial-use criteria[2]							
	0.0164	40	1,000	35	1,500	4,800	[3]20
Carson River	(0.0022)	(16)	(360)	(NC)	(55)	(240)	(3.4)
	0.0005-0.0094	7-45	110-730	<1-<1	22-92	152-503	2.3-9.1
	(0/9)	(1/9)	(0/9)	(0/8)	(0/7)	(0/9)	(0/7)
Drains entering Lead Lake	(0.0065)	(56)	(3,750)	(NC)	(810)	(2,700)	(83)
	0.0008-0.030	11-250	190-31,000	<1-1	58-10,000	282-29,800	2.2-470
	(5/27)	(16/26)	(19/26)	(0/26)	(11/23)	(12/27)	(13/19)
Lead Lake	(0.021)	(84)	(4,000)	(NC)	(905)	(3,200)	(45)
	0.0033-0.19	31-150	2,600-9,600	<1-<1	490-1,800	1,890-15,500	35-61
	(7/11)	(10/12)	(12/12)	(0/12)	(1/10)	(4/13)	(8/8)
Other drains entering SWMA	(0.0089)	(72)	(3,600)	(NC)	(1,100)	(1,900)	(32)
	0.0004-0.11	25-380	560-260,000	<1-21	120-41,000	338-120,000	12-400
	(8/23)	(20/24)	(20/24)	(0/27)	(8/19)	(7/25)	(13/17)
Other lakes in SWMA	(0.020)	(150)	(8,700)	(NC)	(2,000)	(5,600)	(48)
	0.0037-0.088	46-1,400	2,300-73,000	<1-7	370-11,000	423-35,000	30-68
	(8/14)	(15/15)	(15/15)	(0/15)	(10/15)	(8/15)	(6/6)

[1] All un-ionized ammonia values were calculated using equations from Thurston and others (1974).

[2] Beneficial-use criteria are described by Hoffman and others (1990).

[3] Proposed drinking-water standard (U.S. Environmental Protection Agency, 1991).

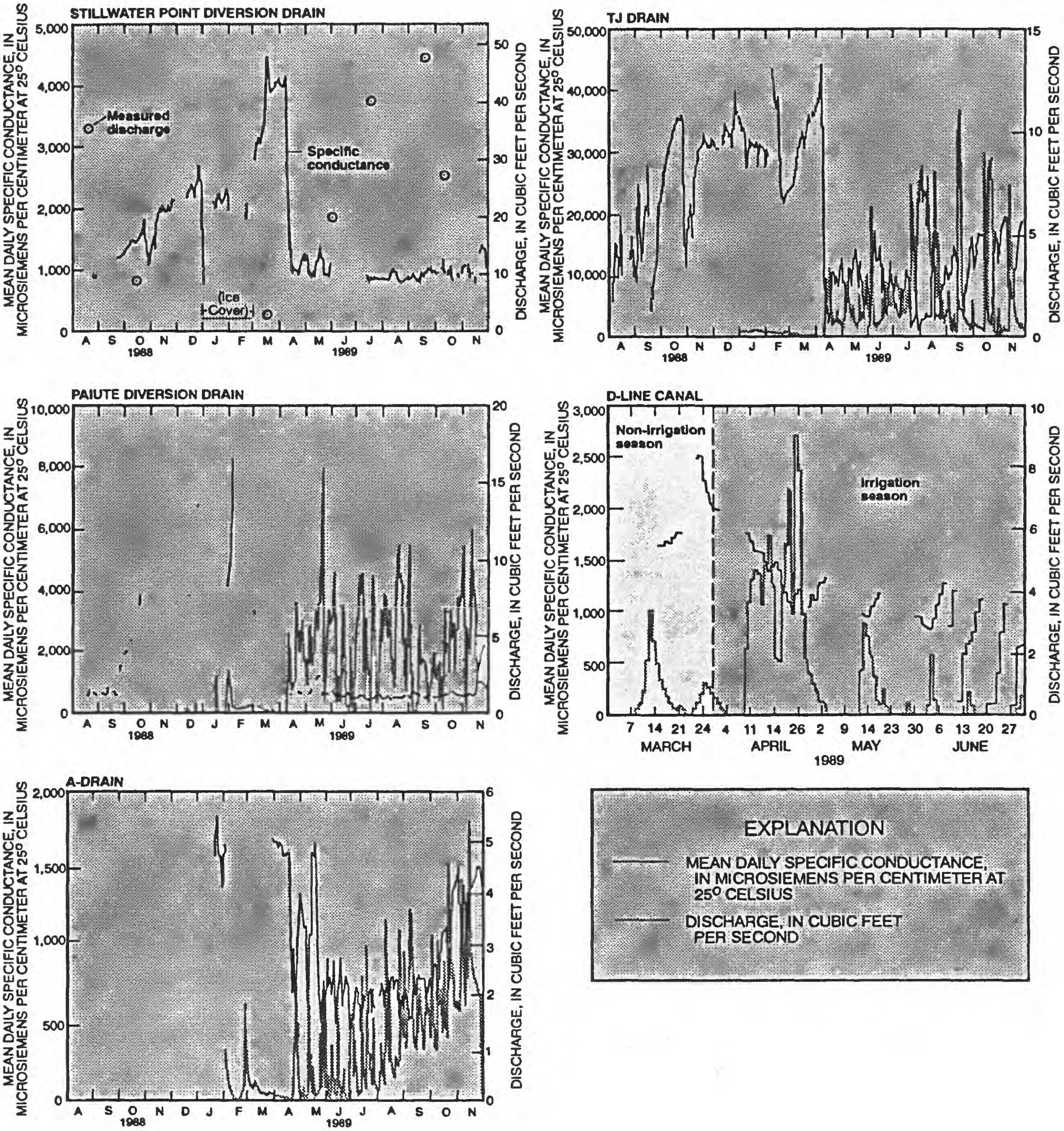

FIGURE 7.--Mean daily specific conductance and discharge as related to time for drains entering Stillwater and Fernley Wildlife Management Areas. Locations are shown in figures 3 and 5.

Stillwater Wildlife Management Area

The quality of water in the Stillwater WMA is highly variable and ranges from dilute precipitation to briny ground water. The Stillwater WMA receives water from several sources, but the major source is irrigation return flow. Water is released from Lahontan Reservoir into the WMA as a precautionary measure during years with greater-than-average precipitation in the headwaters of the Carson River. Several flowing wells that are completed in deeper artesian aquifers also contribute water directly into canals in the WMA. Finally, direct precipitation accounts for a small part of the inflow to Stillwater WMA.

Surface Water

The water used for irrigation is derived from the Carson and Truckee Rivers, stored in Lahontan Reservoir, and released to a network of canals for distribution in the Fallon agricultural area. Occasionally, some of this water flows directly to the Stillwater WMA, but normally all of it is diverted for irrigation in the Fallon agricultural area. The water released from Lahontan Reservoir is a dilute (dissolved solids, 152-503 mg/L) calcium-sodium-bicarbonate or sodium-sulfate type water. During 1986-89, concentrations of dissolved solids generally were greater at lower flows than at higher flows (flows in the Carson River immediately below Lahontan Dam ranged from 1.3 to 1,880 ft^3/s at sampling times during 1986-89). Constituents of concern were present in measurable concentrations in samples collected from the Carson River below Lahontan Reservoir (table 1), but generally were below criteria (Hoffman and others, 1990). Exceptions include one sample that exceeded the Nevada aquatic life criterion for arsenic (40 μg/L); it had a concentration of 45 μg/L. Mercury concentrations in three samples (0.1, 0.2, and 0.3 μg/L) exceeded criteria for the propagation of wildlife (0.05 μg/L). Selenium concentrations were below the analytical reporting level (1 μg/L) in all samples.

Irrigation return flow is collected in a series of unlined ditches that lace the Fallon agricultural area. The major drains that carry the bulk of the water to the marsh are Stillwater Point Diversion, TJ, Paiute Diversion, and Hunter Drains, and D-Line Canal and Stillwater Slough (fig. 2). The quality of water carried by these drains is variable. Table 1 shows the ranges of concentrations of selected constituents in samples from these drains during this study. Not only are concentrations and flows variable throughout the year in these drains, but concentrations can change by as much as an order of magnitude in 24 hours in response to rapid changes in the magnitude of flow (see fig. 7).

Drains Entering Lead Lake

Lead Lake receives water from irrigated land by way of the Paiute Diversion and TJ Drains and D-Line Canal. Dissolved solids, un-ionized ammonia, arsenic, boron, sodium, and uranium exceeded criteria for beneficial use in many cases (table 1). Paiute Diversion Drain carries irrigation return flow that ranges from a dilute (dissolved solids, 282 mg/L) sodium-bicarbonate ($Na\text{-}HCO_3$) type to a very saline (dissolved solids, 13,300 mg/L) sodium-chloride (Na-Cl) type. Temperatures ranged from 0.5 to 29.0°C, pH from 8.4 to 10.0, and dissolved oxygen from 93 to 202 percent saturation for water samples collected from Paiute Diversion Drain (during 1986-87). TJ Drain carries water with high concentrations of potentially toxic constituents such as un-ionized ammonia, arsenic, boron, and uranium from irrigated land in and surrounding the Fallon Indian Reservation. During 1986-89, water in TJ Drain ranged from a slightly saline (dissolved solids, 2,700 mg/L) to a very saline (dissolved solids, 29,800 mg/L) Na-Cl type. Temperatures ranged from 0.0 to 30.5°C, pH from 8.1 to 8.8, and dissolved oxygen from 62 to 235 percent saturation for drain water in TJ Drain. Water delivered by the D-Line Canal is from the Indian Lakes area and, during 1986-89, ranged from a dilute (dissolved solids, 390 mg/L) $Na\text{-}HCO_3$ type to a slightly saline (dissolved solids, 1,050 mg/L) sodium-sulfate ($Na\text{-}SO_4$) type. Temperature ranged from 10.5 to 21.5°C, pH from 9.0 to 9.6, and dissolved oxygen from 114 to 239 percent saturation in water samples from D-Line Canal.

Lead Lake

Water samples collected from Lead Lake during 1986-89 ranged from a slightly saline (dissolved solids, 1,890 mg/L) to a very saline (dissolved solids, 15,500 mg/L) Na-Cl type. Temperature ranged from 2.5 to 32°C, pH from 8.8 to 9.5, and dissolved oxygen from 42 to 303 percent saturation. Un-ionized ammonia, arsenic, and boron most commonly exceeded beneficial-use criteria (table 1).

Other Drains Entering Stillwater Wildlife Management Area

Water samples were collected from three drains that do not empty into Lead Lake, as part of the continued monitoring of sites from the reconnaissance study of 1986-87 (Hoffman and others, 1990). These drains are Stillwater Slough, Stillwater Point Diversion Drain, and Hunter Drain (fig. 2). Median concentrations, ranges of concentrations, and number of samples that exceeded beneficial-use criteria for constituents of concern at Stillwater WMA are shown in table 1. During 1986-89, water collected from Stillwater Slough ranged from a dilute (dissolved solids, 595 mg/L) Na-HCO_3 type to a moderately saline (dissolved solids, 4,210 mg/L) Na-Cl type. Temperature ranged from 7.0 to 25°C, pH from 7.7 to 8.8, and dissolved oxygen from 61 to 136 percent saturation for drain water from Stillwater Slough. Water samples from Stillwater Point Diversion Drain collected during 1986-89 ranged from a dilute (dissolved solids, 338 mg/L) Na-HCO_3 type to a slightly saline (dissolved solids, 2,600 mg/L) Na-Cl type. Temperature ranged from 1.0 to 26.5°C, pH from 7.9 to 9.3, and dissolved oxygen from 57 to more than 200 percent saturation for drain-water samples from Stillwater Point Diversion Drain. Hunter Drain contains water with the highest concentrations of potentially toxic constituents that enters Stillwater WMA. Water samples collected during 1986-89 from Hunter Drain ranged from a moderately saline to a briny (dissolved solids, 3,270 to 120,000 mg/L) Na-Cl type. During 1986-89, temperature ranged from 9.5 to 28.0°C, pH from 7.7 to 9.0, and dissolved oxygen from 2 to 201 percent saturation in water samples from Hunter Drain.

Other Lakes in Stillwater Wildlife Management Area

Six other lakes were sampled to obtain more baseline water-quality data than that obtained by Hoffman and others (1990). The lakes are East Alkali, Goose, and Cattail Lakes, Stillwater Point Reservoir, Swan Check, and Pintail Bay (fig. 2). These are important water bodies in the management area because they are used extensively by waterfowl. The lakes represent the entire range of unit types, from primary (those that receive the most dilute water), such as Stillwater Point Reservoir, to tertiary (the most saline water bodies used by waterfowl), such as Pintail Bay. Concentrations of constituents of concern commonly exceeded beneficial-use criteria in most of these lakes (table 1).

Stillwater Point Reservoir receives irrigation drainage by way of Stillwater Point Diversion Drain. Water samples collected from Stillwater Point Reservoir ranged from a dilute (dissolved solids, 423 mg/L) Na-SO_4 type to a slightly saline (dissolved solids, 1,890 mg/L) Na-Cl type. Temperature ranged from 7.5 to 27°C, pH from 8.0 to 10.0, and dissolved oxygen from 76 to 241 percent saturation for water samples from Stillwater Point Reservoir during 1986-89. Water samples from East Alkali Lake collected during this study were a slightly to moderately saline (dissolved solids, 2,680 to 6,900 mg/L) Na-Cl type. Temperature ranged from 8.5 to 24.5°C, pH from 9.4 to 10.4, and dissolved oxygen from 93 to 198 percent saturation for water samples from East Alkali Lake during 1986-89. Water samples from Swan Check ranged from a slightly to a moderately saline (dissolved solids, 2,610 to 5,570 mg/L) Na-Cl type. During 1986-89, temperature ranged from 8.0 to 29.5°C, pH from 8.7 to 9.5, and dissolved oxygen from 99 to greater than 300 percent saturation in water samples from Swan Check. Water in Cattail Lake ranged from a moderately to very saline (dissolved solids, 4,000 to 10,800 mg/L) Na-Cl type. Temperature ranged from 8.5 to 18.5°C, pH from 8.9 to 9.7, and dissolved oxygen from 79 to 99 percent saturation in water samples from Cattail Lake. A very saline (dissolved solids, 10,300 mg/L) Na-Cl type water was present at the single sampling time at Goose Lake. Temperature and pH were measured twice; temperature values were 4.0 and 24°C and pH was 9.3 and 9.6 in water samples from Goose Lake. One dissolved-oxygen concentration was measured at 278 percent saturation. The most saline water body sampled in Stillwater WMA during this study (1988-89) was Pintail Bay, which is a tertiary unit at the Management Area (Hoffman and others, 1990, p. 14). Water samples were very saline (dissolved solids, 12,200 to 35,000 mg/L) and were Na-SO_4 or Na-Cl types. Temperatures at sampling times ranged from 15.5 to 19.5°C, pH was 9.4 at both sampling times, and dissolved oxygen ranged from 30 to 119 percent saturation.

Dissolved-Solids Loads Entering Stillwater Wildlife Management Area

Loads of dissolved solids and potentially toxic constituents entering Stillwater WMA are important in determining which parts of the Fallon agricultural area contribute the highest proportion of these elements. The U.S. Fish and Wildlife Service needs this type of information to evaluate mitigation alternatives. To this end, broad areas within the Fallon agricultural area are identified in this report as to their contribution to the total load of dissolved constituents entering the marsh.

Loads of dissolved solids were calculated for six drains and canals entering Stillwater WMA (table 2). Stream gages and specific-conductance monitors that record hourly readings of discharge and specific conductance were placed in three of the channels. Regression equations were developed for the instantaneous measurements of specific conductance and dissolved-solids concentration. In addition to dissolved solids, boron and sodium also correlated well with specific conductance (r^2 >0.95), but other constituents of concern (arsenic, mercury, lithium, uranium, and un-ionized ammonia) did not. At Hunter and Stillwater Point Diversion Drains and Stillwater Slough, mean loads were calculated using instantaneous measurements of specific conductance and dissolved solids instead of hourly measurements, and therefore should be considered as rough estimates.

The actual number of acres served by each major drain has not been determined and may be impossible to ascertain (Gene A. Harms, U.S. Bureau of Reclamation, oral commun., 1990); thus yields can only be qualitatively discussed. The calculated loads of dissolved solids (table 2) indicate that Stillwater Point Diversion Drain, Stillwater Slough, and TJ Drain contributed more than 80 percent of the load to Stillwater WMA during 1988-89. Stillwater Point Diversion Drain serves much of the central Fallon agricultural area, an area of much greater acreage than that served by the other drains, and carries about 41 percent of the dissolved-solids load to Stillwater Wildlife Management Area. Thus, the yield of dissolved solids, in tons per day per acre, actually is less than that for TJ Drain and Stillwater Slough drainage areas.

TJ Drain serves a small part of the Fallon Indian Reservation (U.S. Bureau of Reclamation, 1987a) that is mostly unirrigated land. The Drain carries about 19 percent of the dissolved-solids load to Stillwater WMA. Because this significant part of the load is derived from a relatively small area, the yield per acre is relatively large. When the dissolved-solids load for TJ Drain is separated by irrigation season (April through October) and nonirrigation season (November through March), it becomes apparent that ground water is a significant component of the flows in TJ Drain (table 2).

About 30 percent of the dissolved-solids load in TJ Drain is derived from ground-water seepage. Hunter Drain, a small service-area drain, carries 8 percent of the total load to Stillwater WMA. About 23 percent of the dissolved-solids load to Stillwater WMA flows through Stillwater Slough. Drainage from agricultural land of unknown size flows into the slough, then on to the Canvasback Gun Club. After being used in the gun club ponds, the water is released to Stillwater WMA, and at that point, it is of unknown quality.

Flow through Paiute Diversion Drain supplies a small part (6 percent) of the total load to Stillwater WMA. Paiute Diversion Drain receives its flow from a part of the Fallon Indian Reservation that has been irrigated for many years, in contrast to the TJ Drain service area as discussed above. Seasonal dissolved-solids loads carried by Paiute Diversion Drain (table 2) show that loads during the nonirrigation season (November through March) were higher than those during the irrigation season. A probable explanation for the large nonirrigation-season load is the release of water from a geothermal well during January 1989. The hydrograph for Paiute Diversion Drain shows peaks in late January and increases in specific conductance (fig. 7). The peak was caused by a blow-out of a geothermal well during drilling and an uncontrolled release of steam and water from the confined geothermal aquifer. Initially, water was sent down a drain into the Canvasback Gun Club, then it was diverted to Paiute Diversion Drain. An earthen dam was placed in Paiute Diversion Drain and water was diverted out onto the bare desert soil. During this time, a significant amount of water seeped through the dam and the side of the drain adjacent to where water was applied to the desert. Analysis of the geothermal effluent revealed that the water was a moderately saline, Na-Cl type with a specific conductance of 8,600 µS/cm. This specific conductance agrees with the values observed downstream at the monitoring site (figs. 3 and 7). Flow rates from the well were estimated to be between 4.5 and 9 ft^3/s. Typical nonirrigation-season loads probably are much less than the 1988-1989 value.

TABLE 2.--*Mean daily loads of dissolved solids*[1] *entering Fernley and Stillwater Wildlife Management Areas through drains servicing agricultural areas, 1986-89*

[Loads are in tons per day; --, data not available]

Drain name	Irrigation season (April-October 1989)	Nonirrigation season (November 1988-March 1989)	Yearly average
	Fernley Wildlife Management Area		
A-Drain[2]	1.29	4.86	2.77
	Stillwater Wildlife Management Area		
D-Line Canal[2]	4.20	2.34	3.43
Hunter Drain[3]	--	--	10
Paiute Diversion Drain[2]	4.53	11.94	7.60
Stillwater Point Diversion Drain[4]	--	--	50
Stillwater Slough[4]	--	--	28
TJ Drain[2]	28.35	16.73	23.5

[1] Dissolved-solids concentrations were calculated by applying the following regression equations to hourly recorded specific-conductance values:

Stillwater Wildlife Management Area

Dissolved solids = $10^{[-0.321 + 1.04\log(\text{specific conductance})]}$;

$r^2 = 0.99$, $\alpha = 0.05$

Fernley Wildlife Management Area

Dissolved solids = $10^{[-0.257 + 1.02\log(\text{specific conductance})]}$;

$r^2 = 0.99$, $\alpha = 0.05$

[2] Mean loads were calculated using the following discharge-weighted equation:

$$L = \frac{\Sigma(C_i Q_i)}{\Sigma Q_i}(0.0027 Q_m);$$

where L = load for the period of interest, in tons per day;

Q_i = instantaneous discharge at the time of sampling, in cubic feet per second;

C_i = concentration at time of sampling, in milligrams per liter; and

Q_m = mean daily discharge for the period, in cubic feet per second.

[3] Calculated from instantaneous measurements during period of 1987-89.

[4] Calculated from instantaneous measurements during period of 1986-89.

D-Line Canal carries water from the Indian Lakes area in the western part of Stillwater WMA. This water is delivered only periodically and contributes a minor part (about 3.4 percent) of the load to Stillwater WMA. The dissolved-solids load carried by D-Line Canal in the irrigation season, as calculated by the discharge-weighted method (table 2), is almost twice as large as the nonirrigation-season load. Specific-conductance values are higher during the nonirrigation season (about 1,500-2,500 μS/cm) than during the irrigation season (about 1,000 μS/cm).

Ground Water

Ground-water samples were collected from the shallow unconfined aquifer and from the confined--including geothermal--aquifers at Stillwater WMA. Samples from five existing wells and one geothermal well were used to define the quality of the deeper, confined water that flows into Stillwater WMA (fig. 3). The composition of water samples is shown in a trilinear diagram, which displays the relative proportion of major ions in water samples, and is described below (fig. 8). Compositions of water samples from unconfined and confined aquifers are distinctly different. All data for sampled ground water were published by Rowe and others (1991).

Unconfined Ground Water

Water in the shallow water-table aquifer ranged from a very saline (dissolved solids, 10,400 mg/L) to a briny (dissolved solids, 94,700 mg/L) Na-Cl type. The temperature of the ground water ranged from 11.0 to 19.5°C and the pH ranged from 6.6 to 7.7. Eh values (measure of oxidation-reduction potential) ranged from reducing voltages (-115 mV) to oxidizing values of 340 mV. Dissolved oxygen ranged from below detection (0.1 mg/L) to 1.4 mg/L. All of the constituents of concern were present at high concentrations in the shallow ground water, with the exception of un-ionized ammonia (concentrations were below the criterion value of 0.0164 mg/L as N, except for one sample that was 0.24 mg/L (table 3)). Water from this well had a reducing potential (Eh, -115 mV) which tends to chemically reduce nitrogen species (NO_3 and NO_2) to ammonia.

Confined Ground Water

Water sampled from the confined aquifer beneath Stillwater WMA ranged from a slightly saline (dissolved solids, 1,400 mg/L) to a moderately saline (dissolved solids, 8,490 mg/L) Na-Cl type (table 3). Water temperatures ranged from 16.5 to 80°C, the latter from a geothermal well near the southwestern part of Stillwater WMA. Dissolved oxygen ranged from 0.2 to 0.6 mg/L (6-8 percent saturation), whereas pH ranged from 7.9 to 8.8. Water from the confined aquifer contained constituents of concern generally at lower concentrations than water from the overlying, unconfined aquifer. Arsenic, boron, sodium, and dissolved solids most commonly exceeded beneficial-use criteria (table 3).

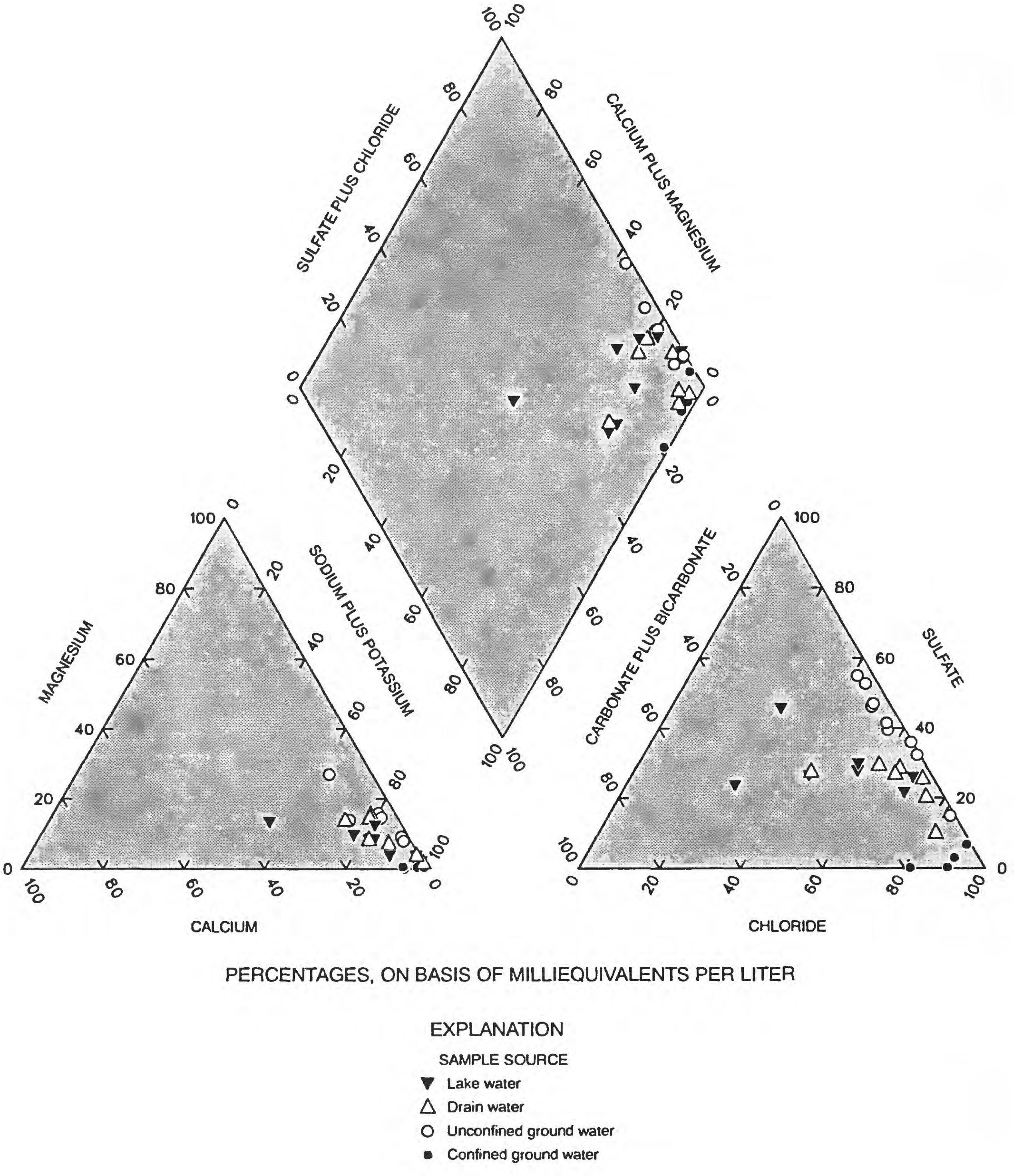

FIGURE 8. --Composition of water samples from lakes, drains, and wells in and near Stillwater Wildlife Management Area.

TABLE 3.--*Statistical summary of dissolved constituents of concern (Hoffman and others, 1990) in ground-water samples from sites in and near Stillwater and Fernley Wildlife Management Areas, 1986-89. For each three-line data group, upper number (in parentheses) is median concentration, middle numbers are minimum and maximum concentrations, and lower numbers (in parentheses) are number of samples exceeding criteria per number of samples analyzed*

[Abbreviations: mg/L, milligrams per liter; N, nitrogen; NC, median value not calculated because more than 50 percent of the concentrations were below analytical reporting level; μg/L, micrograms per liter; <, less than; --, no data available]

Site	Un-ionized ammonia (mg/L as N)[1]	Arsenic (μg/L)	Boron (μg/L)	Selenium (μg/L)	Sodium (mg/L)	Dissolved solids (mg/L)	Uranium (μg/L)
			Beneficial-use criteria[2]				
	0.0164	40	1,000	35	1,500	4,800	[3]20
			Stillwater Wildlife Management Area				
Shallow aquifer	(0.0046) 0.0007-0.24 (1/13)	(420) 37-1,400 (29/30)	(57,000) 14,000-120,000 (30/30)	(NC) <1-110 (4/30)	(9,100) 2,300-30,000 (30/30)	(34,000) 10,400-94,700 (30/30)	(200) 1.9-1,500 (27/29)
Confined aquifer (including geothermal)	(--) 1.4 (1/1)	(21) 2-130 (2/5)	(19,000) 12,000-23,000 (6/6)	(NC) <1-<1 (0/4)	(1,550) 520-3,100 (3/6)	(4,400) 1,400-8,490 (2/6)	(3.8) <0.4-5.6 (0/3)
			Fernley Wildlife Management Area				
Shallow aquifer	(NC) <0.0001-0.0016 (0/17)	(300) <1-1,200 (23/27)	(1,200) 370-3,400 (17/27)	(NC) <1-10 (0/27)	(230) 20-760 (0/27)	(660) 335-2,230 (0/27)	(5.2) 3.1-41 (2/20)
Confined aquifer (including geothermal)	(0.0033) 0.0021-0.053 (1/7)	(46) 25-65 (7/9)	(4,650) 1,600-13,000 (10/10)	(NC) <1-<1 (0/9)	(1,000) 640-5,100 (4/10)	(3,200) 2,170-16,500 (4/9)	(4.1) 0.5-40 (1/7)

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[1] All un-ionized ammonia values were calculated using equations from Thurston and others (1974).

[2] Beneficial-use criteria are described by Hoffman and others (1990).

[3] Proposed drinking-water standard (U.S. Environmental Protection Agency, 1991).

Stable Isotopes

Stable isotopes[1] commonly are used as part of comprehensive hydrologic studies of processes controlling water quality and sources of water and its dissolved constituents. Physical and biologic processes fractionate stable isotopes, leaving distinct patterns of isotopic composition of compounds in the aqueous and solid phases. Hydrogen ($^2H/^1H$) and oxygen ($^{18}O/^{16}O$) isotopes of water can be used to identify sources of recharge, water-rock interaction processes, and evaporation. Deverel and Fujii (1988) used the isotopes of water to determine the history of shallow ground water associated with agricultural drainage in the San Joaquin Valley of California. Stable isotopes of carbon ($^{13}C/^{12}C$) can be used to identify sources of and processes that produce dissolved bicarbonate. Those sources and processes include atmospheric and soil-zone CO_2, dissolved and sedimentary organic carbon, or carbonate minerals in the aquifer and biologic reactions such as sulfate reduction (see equation 4 in section "Hydrogeochemical processes affecting surface-water quality"). Sulfur isotopes ($^{34}S/^{32}S$) can be used to identify the source of dissolved sulfur species (H_2S, SO_4^{2-}) in ground water and the processes controlling their concentrations (sulfate reduction, mineral dissolution, or mineral precipitation). Both carbon and sulfur isotopes can be used to independently verify the feasibility of geochemical reactions proposed in ground-water models.

Shallow ground water from the Stillwater WMA has been highly evaporated from its original recharge state. Figure 9 is a graph plotting delta deuterium (δD) as related to delta oxygen-18 ($\delta^{18}O$) that shows a trend with a slope of 4.7 permil, which is typical of evaporation (Fontes, 1980, p. 78). Water from the deeper confined aquifer (artesian wells) is on the same trend, closest to the meteoric water line of Craig (1961) which suggests a similar recharge source. Well LLAH-3 is located adjacent to the Paiute Diversion Drain (fig. 3) and apparently is influenced by seepage of less saline water from the drain, as shown by the low chloride concentration in figure 10. The other ground-water samples follow a vaguely defined trend of decreasing δD (heavier) with increasing chloride content.

The delta sulfur-34 ($\delta^{34}S$) concentration in ground-water samples from the Lead Lake area in Stillwater WMA ranged from +3.5 to +5.6 permil. These isotopic compositions possibly were derived from a combination of dissolution of reduced sulfur minerals in volcanic rocks ($\delta^{34}S$ near 0 permil) and evaporite minerals in the soil such as gypsum ($CaSO_4 \cdot 2H_2O$) and thenardite (Na_2SO_4) with a $\delta^{34}S$ greater than +10 permil. Another possible explanation for the $\delta^{34}S$ of ground water could be the dissolution of reduced sulfur minerals in volcanic rocks ($\delta^{34}S$ near 0 permil) and localized precipitation of a sulfide phase (FeS) within the clayey sediment which would leave the aqueous phase enriched in ^{34}S because of partitioning of light sulfur in the sulfide phase. These localized reducing zones are indicated by mottling in the clayey parts of the sediment.

Surface water in Stillwater WMA has a $\delta^{34}S$ range of +4.8 to +8.0 permil and is slightly enriched in ^{34}S compared to the ground water. Active production of hydrogen sulfide by sulfate reduction and precipitation of sulfide as ferrous monosulfide (FeS) could easily account for this slight enrichment of ^{34}S in the aqueous phase. Sulfate reduction most likely is occurring in the bottom sediment of Lead Lake and TJ Drain where black, hydrogen-sulfide-rich sediment is present.

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[1] The stable isotopes evaluated herein are carbon-13 relative to carbon-12 ($^{13}C/^{12}C$), deuterium (hydrogen-2) relative to hydrogen-1 ($D/^1H$), oxygen-18 relative to oxygen-16 ($^{18}O/^{16}O$), and sulfur-34 relative to sulfur-32 ($^{34}S/^{32}S$). Each ratio is determined for a water sample, and then related mathematically to the comparable ratio for the following international reference standards: Peedee belemnite for carbon, Vienna Standard Mean Ocean Water for hydrogen and oxygen, and Canyon Diablo Troilite for sulfur isotopes. By convention, the computed results are expressed as "delta carbon-13," "delta deuterium," "delta oxygen-18," and "delta sulfur-34"; the units of measure are parts per thousand (abbreviated "permil"). A negative delta value indicates that the water sample is isotopically lighter than the standard; for example, the water sample has a smaller proportion of deuterium, relative to hydrogen-1, compared to the standard.

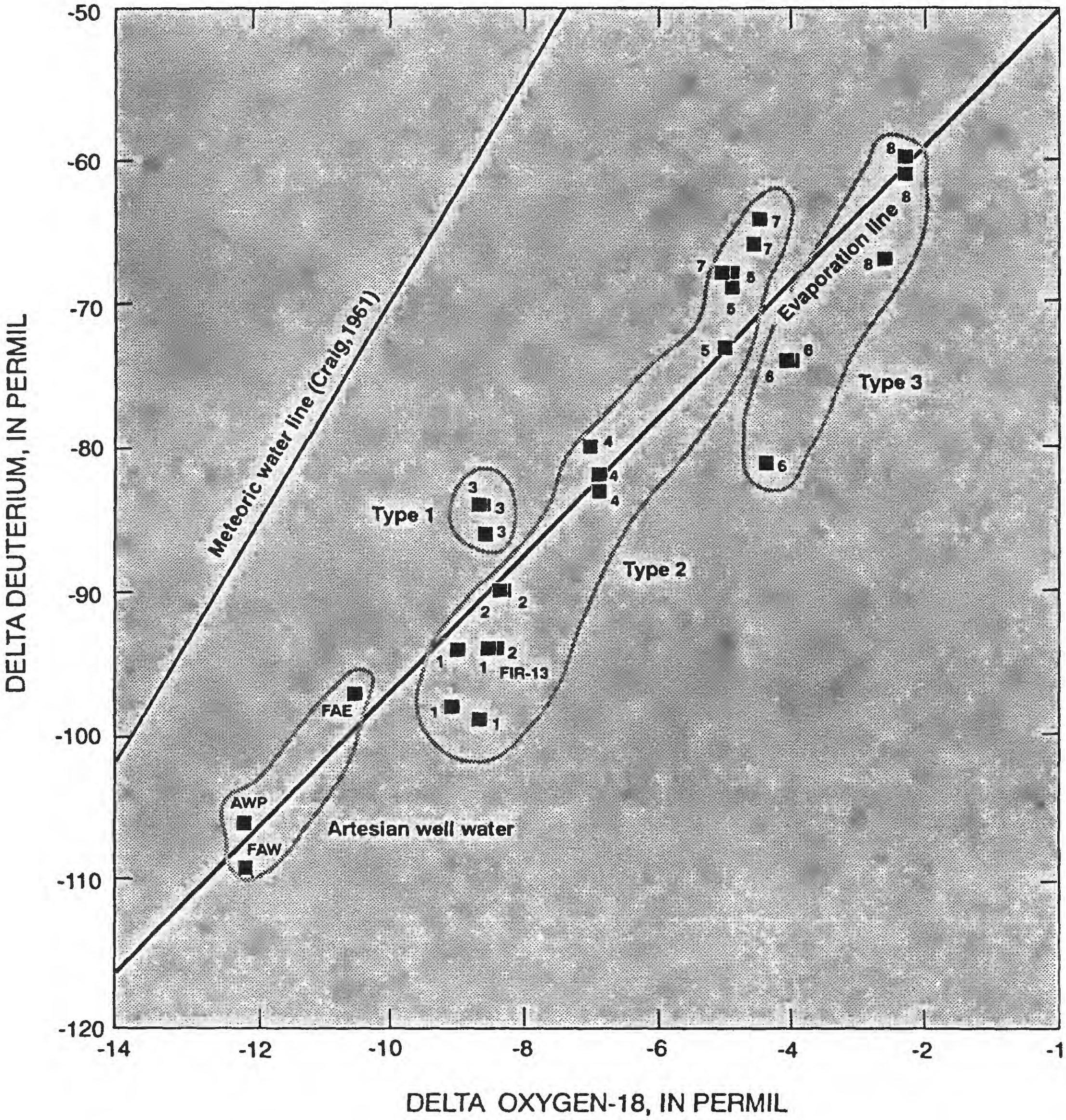

FIGURE 9. --Delta oxygen-18 as related to delta deuterium for water samples collected from wells in Stillwater Wildlife Management Area. Letters and numbers indicate sites shown in figures 2 and 3. Water types (1, 2, and 3) are defined in the section "Hydrogeochemical processes affecting ground-water composition" of this report.

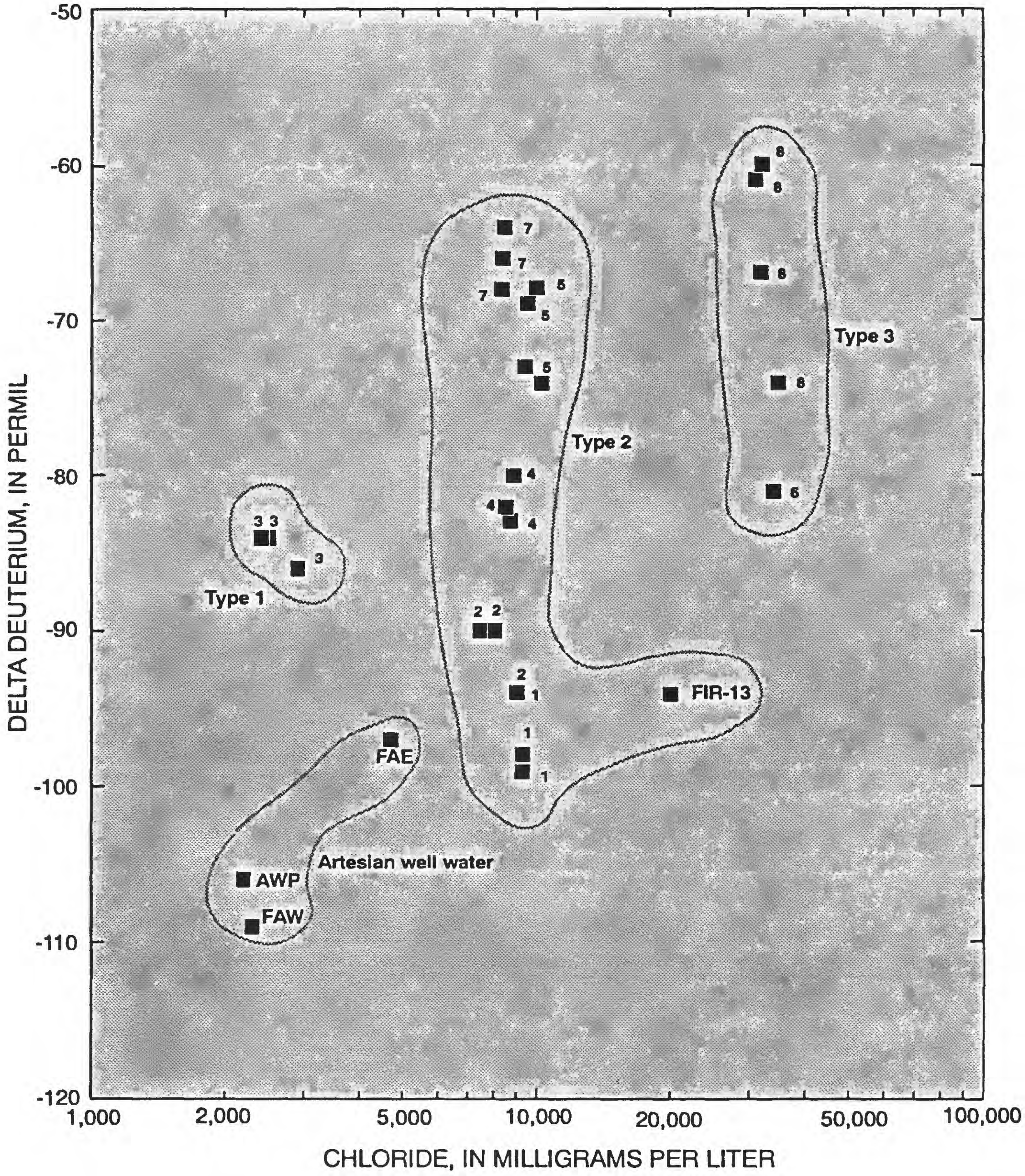

FIGURE 10. --Delta deuterium as related to chloride concentrations for water samples collected from wells in Stillwater Wildlife Management Area. Letter and number symbols represent sites shown in figures 2 and 3. Types (1,2, and 3) are defined in the section "Hydrogeochemical processes affecting ground-water composition" of this report.

The isotopic composition of dissolved inorganic carbon, expressed as delta carbon-13 ($\delta^{13}C$), in ground water at Stillwater WMA ranges from -6.1 to -10.6 permil. These isotopic compositions are slightly heavier than those typical of HCO_3^- produced by the soil gas CO_2 or the decomposition of organic matter. Calcite, of unknown $\delta^{13}C$, is present in the soils within Stillwater WMA and is precipitated on existing calcite shell fragments, as seen in thin section (fig. 11). Dissolution of this calcite, which probably has a $\delta^{13}C$ near zero, could produce the observed values.

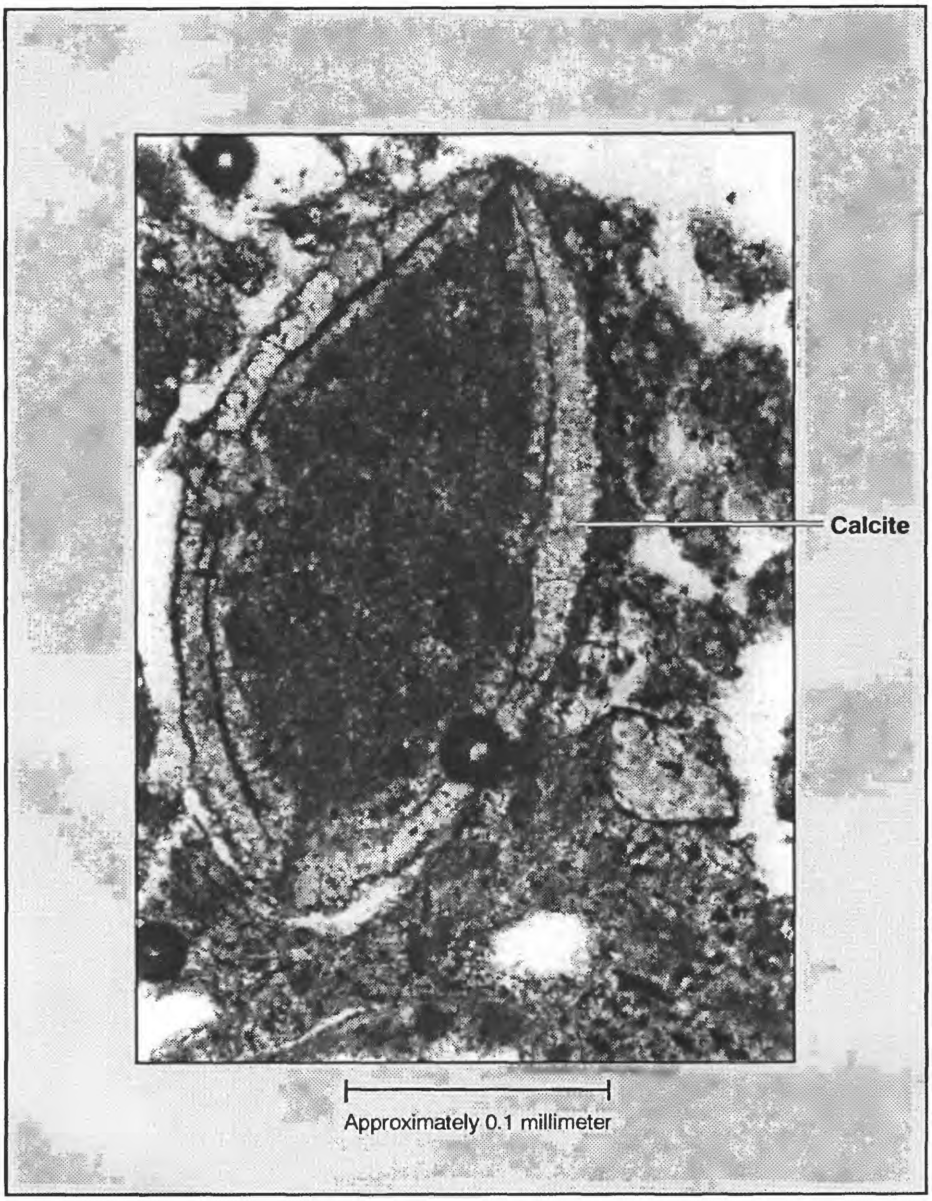

FIGURE 11. --Calcite precipitated on shell fragments in Pleistocene lake sediment from Stillwater Wildlife Management Area. Photomicrograph by Patrick Goldstrand, U.S. Geological Survey, November 1990.

The $\delta^{13}C$ of dissolved HCO_3^- in surface waters of Stillwater WMA ranged from -13.3 permil in the Paiute Diversion Drain to -1.6 permil in Lead Lake. The value for Paiute Diversion Drain is close to the values found for shallow ground water beneath an irrigated field south of Fallon (Lico and others, 1987). Paiute Diversion Drain receives its water from irrigated land in and near the Fallon Indian Reservation. The $\delta^{13}C$ of TJ Drain is -8.0 permil, which is similar to the ground water $\delta^{13}C$ value (average -7.7 permil) found near Lead Lake. TJ Drain is a deep (maximum depth, about 15 ft), newly constructed (1983) drain that intercepts the water table and drains water from beneath unirrigated native vegetation. Water in Lead Lake is heavier in $\delta^{13}C$ (-1.6 permil) than both input waters (TJ and Paiute Diversion Drains), indicating that processes affecting the carbon species in the water are taking place. Reduction of HCO_3^- to CH_4 by bacterial action is the most likely process responsible for the observed isotopic composition of Lead Lake water. Bacteria will preferentially use the lighter isotope (^{12}C), which leaves a greater proportion of heavy isotope (^{13}C) in the water. Data presented by Rowe and others (1991) indicate that sulfate concentrations are near zero a few inches below the sediment-water interface in some drains. This would allow methane production by the microbial community present in the sediment.

Fernley Wildlife Management Area

The Fernley WMA receives water mainly through leakage from the Truckee Canal and irrigation-return flow from the agricultural area in the southern part of the Fernley basin (see section on "Hydrologic setting"). Minor sources of water include discharge from a hot spring in the southeastern part of the WMA, upward leakage of confined ground water, and precipitation.

Surface Water

Water used for irrigation in the Fernley agricultural area is diverted from the Truckee River by way of the Truckee Canal. This water was a dilute (dissolved solids, 113-180 mg/L) calcium- to sodium-bicarbonate (Ca- to $Na\text{-}HCO_3$) type with a pH ranging from 7.2 to 8.7. Water temperatures at sampling times ranged from 9.0 to 24.5°C, and dissolved oxygen was near saturation (78 to 122 percent saturation). Constituents of concern, as described by Hoffman and others (1990), were present at low levels. Only one sample from the canal exceeded the beneficial-use criteria described by Hoffman and others (1990); un-ionized ammonia concentrations were as much as 0.076 mg/L, which is greater than the criteria value of 0.0164 mg/L (see table 4).

Drains Entering Fernley Wildlife Management Area

Three major drains serve the Fernley agricultural area. These are A-Drain, Fernley Drain, and Streiff Drain. Fernley and Streiff Drains discharge to A-Drain near the southwestern edge of the Fernley WMA; A-Drain flows into South Pond in the management area (fig. 5). A-Drain, above the confluence of Fernley and Streiff Drains, carries water that is a dilute (dissolved solids, 168 mg/L) $Ca\text{-}HCO_3$ type to a slightly saline (dissolved solids, 1,040 mg/L) $Na\text{-}SO_4$ type. Temperatures ranged from 4.5 to 19.0°C, pH from 7.0 to 8.4, and dissolved oxygen from 65 to 133 percent saturation (6.1 to 12.9 mg/L) at the times that samples were collected. Fernley Drain flows intermittently and contains water that is a dilute (dissolved solids, 544 to 605 mg/L) $Na\text{-}HCO_3$ type. Temperature ranged from 13.0 to 14.0°C, pH from 7.5 to 7.7, and dissolved oxygen from 60 to 78 percent saturation (5.2 to 7.0 mg/L). Water in Streiff Drain is a dilute (dissolved solids, 473 to 563 mg/L) $Na\text{-}HCO_3$ type with a pH ranging from 7.7 to 9.0. Temperature ranged from 11.0 to 17.0°C and dissolved oxygen from 86 to 112 percent saturation (7.7 to 10.5 mg/L).

Downstream from the confluence of A-, Fernley, and Streiff Drains, the quality of water in A-Drain represents a mixture of the three drains plus a contribution from the shallow ground-water system. The water in this part of A-Drain is a dilute (dissolved solids, 501 mg/L) $Na\text{-}HCO_3$ type to a slightly saline (dissolved solids, 1,320 mg/L) $Na\text{-}SO_4$ type. Temperature ranged from 0 to 26.5°C at sampling times during 1987-89. Dissolved oxygen ranged from 50 to 168 percent saturation (4.1 to 14.5 mg/L) and pH from 7.7 to 8.6.

TABLE 4.--*Statistical summary of dissolved constituents of concern (Hoffman and others, 1990) in surface-water samples from sites in and near Fernley Wildlife Management Area, 1987-89. For each three-line data group, upper number (in parentheses) is median concentration, middle numbers are minimum and maximum concentrations, and lower numbers (in parentheses) are number of samples exceeding criteria per number of samples analyzed*

[Abbreviations: FWMA, Fernley Wildlife Management Area; mg/L, milligrams per liter; N, nitrogen; NC, median value was not calculated because more than 50 percent of the concentrations were below analytical reporting level; μg/L, micrograms per liter; <, less than]

Sites	Un-ionized ammonia (mg/L as N)[1]	Arsenic (μg/L)	Boron (μg/L)	Selenium (μg/L)	Sodium (mg/L)	Dissolved solids (mg/L)	Uranium (μg/L)
			Beneficial-use criteria[2]				
	0.0164	40	1,000	35	1,500	4,800	[3]20
Truckee Canal	(0.0032) 0.0004-0.076 (1/28)	(7.0) 5.0-8.0 (0/5)	(180) 110-430 (0/6)	(NC) <1-<1 (0/5)	(18) 12-27 (0/6)	(130) 113-180 (0/6)	(1.0) 0.80-1.2 (0/4)
Drains entering FWMA	(0.0011) 0.0002-0.015 (0/21)	(74) 7.0-460 (16/22)	(760) 180-6,000 (4/22)	(NC) <1-3 (0/22)	(130) 20-1,000 (0/22)	(530) 168-2,920 (0/22)	(5.0) 0.50-14 (0/15)
Ponds in FWMA	(0.0091) 0.0013-0.134 (3/9)	(435) 150-7,500 (12/12)	(11,000) 2,500-61,000 (12/12)	(NC) <1-12 (0/15)	(2,500) 560-16,000 (9/12)	(8,100) 1,860-45,100 (9/12)	(110) 20-380 (9/9)

[1] All un-ionized ammonia values were calculated using equations from Thurston and others (1974).

[2] Beneficial-use criteria are described by Hoffman and others (1990).

[3] Proposed drinking-water standard (U.S. Environmental Protection Agency, 1991).

One sample was collected from a small channel on the northern side of the Fernley basin that flows into the Fernley Sink. This channel, known as Bradys Creek, contains discharge from a vegetable-dehydration plant that utilizes water from the Bradys Hot Springs geothermal system. At the time of sampling, water in this channel (about 3 mi downstream from the source) was a slightly saline (dissolved solids, 2,920 mg/L) Na-Cl type with a temperature of 10.0°C and a pH of 8.3. Dissolved oxygen was near saturation (98 percent) at 9.3 mg/L.

Water in the drains exceeded beneficial-use criteria for arsenic (16 of 22 samples) and boron (4 of 22 samples). Arsenic ranged from 7.0 to 460 μg/L in drain-water samples (median concentration, 74 μg/L; table 4). Boron concentrations ranged from 180 to 6,000 μg/L (median concentration, 760 μg/L). All other elements of concern (un-ionized ammonia, sodium, dissolved solids, and uranium) were below criteria values. Selenium concentrations ranged from less than 1 to 3 μg/L; most were less than 1 μg/L.

Ponds in and near Fernley Wildlife Management Area

Fernley WMA consists of a series of shallow, flow-through ponds that hold increasingly saline water downward through the flow system (fig. 5). The first pond in this series is South Pond, which contains variable-quality water ranging from a moderately to very saline (dissolved solids, 4,400 to 20,600 mg/L) Na-SO_4 type. The pH of water from South Pond was fairly constant, ranging from 8.9 to 9.3, and the temperatures were between 5.0 and 32°C at the sampling times. Dissolved oxygen ranged from 85 to 249 percent saturation (8.5-20 mg/L). North Pond receives inflow from South Pond and contains water that ranges from a slightly to moderately saline (dissolved solids, 1,860 to 5,040 mg/L) Na-SO_4 type. Temperatures ranged from 10.5 to 12.0°C, pH from 8.9 to 9.3, and dissolved oxygen from 97 to 193 percent saturation (9.1 to 17.6 mg/L) during sampling times. Northeast Pond also receives water from South Pond, by way of another outlet, and contains water with the highest concentrations of potentially toxic constituents in the Fernley WMA, aside from the Fernley Sink. Water in Northeast Pond ranged from a moderately saline (dissolved solids, 6,690 mg/L) Na-SO_4 type to a briny (dissolved solids, 45,100 mg/L) Na-Cl type. These water samples were very alkaline, ranging in pH from 8.9 to 9.8. Dissolved oxygen ranged from 102 to greater than 370 percent saturation (from 9.1 to >20 mg/L) and temperatures were from 9.5 to 30°C.

A small pond north of Fernley WMA along the western edge of Interstate 80, here termed Freeway Pond, contains water that discharges from springs along the base of the Truckee Range and possibly from upward flow through the playa sediment of Fernley Sink. The water in Freeway Pond is a very saline (dissolved solids, 11,600-25,600 mg/L) Na-Cl type with pH values constant at 8.8. Temperature ranged from 11 to 16.5°C and dissolved oxygen from 108 to 131 percent saturation (9.1 to 10.2 mg/L). Except for selenium, water in the ponds of Fernley WMA generally exceeded beneficial-use criteria for constituents of concern (see table 4).

Dissolved-Solids Loads Entering Fernley Wildlife Management Area

In the Fernley area, A-Drain below the confluence of A-, Streiff, and Fernley Drains delivers virtually all the surface water that enters the Fernley WMA. The median dissolved-solids load is much less than in any single drain at Stillwater WMA, about 2.8 ton/d (table 2). Loads were not calculated for each contributing drain to A-Drain for this study. Figure 7 shows mean daily discharge and specific conductance as a function of time. During the nonirrigation season (November-March), specific conductance is about 1,500 µS/cm and probably represents ground-water seepage into A-Drain. During the irrigation season (April-October), specific conductance drops to about 700 µS/cm, then gradually increases in September and October. The increase (during September and October) in specific conductance is accompanied by an increase in mean daily discharge (fig. 7) and probably represents an increase in the amount of seepage from the shallow ground water as the water table rises.

Ground Water

Ground water was sampled from the shallow unconfined aquifer that is recharged from leakage of the Truckee Canal and by infiltration of water from irrigation of alfalfa fields and pastures in the Fernley agricultural area. Ten wells (fig. 5) were sampled in an effort to characterize the quality of this water-table aquifer. In addition, two wells and one hot spring were sampled to define the quality of water from the confined aquifer beneath Fernley WMA. The compositions of the water samples from all 13 sites are shown in a trilinear diagram (fig. 12) and are described below. All data for sampled ground water were published in a report by Rowe and others (1991).

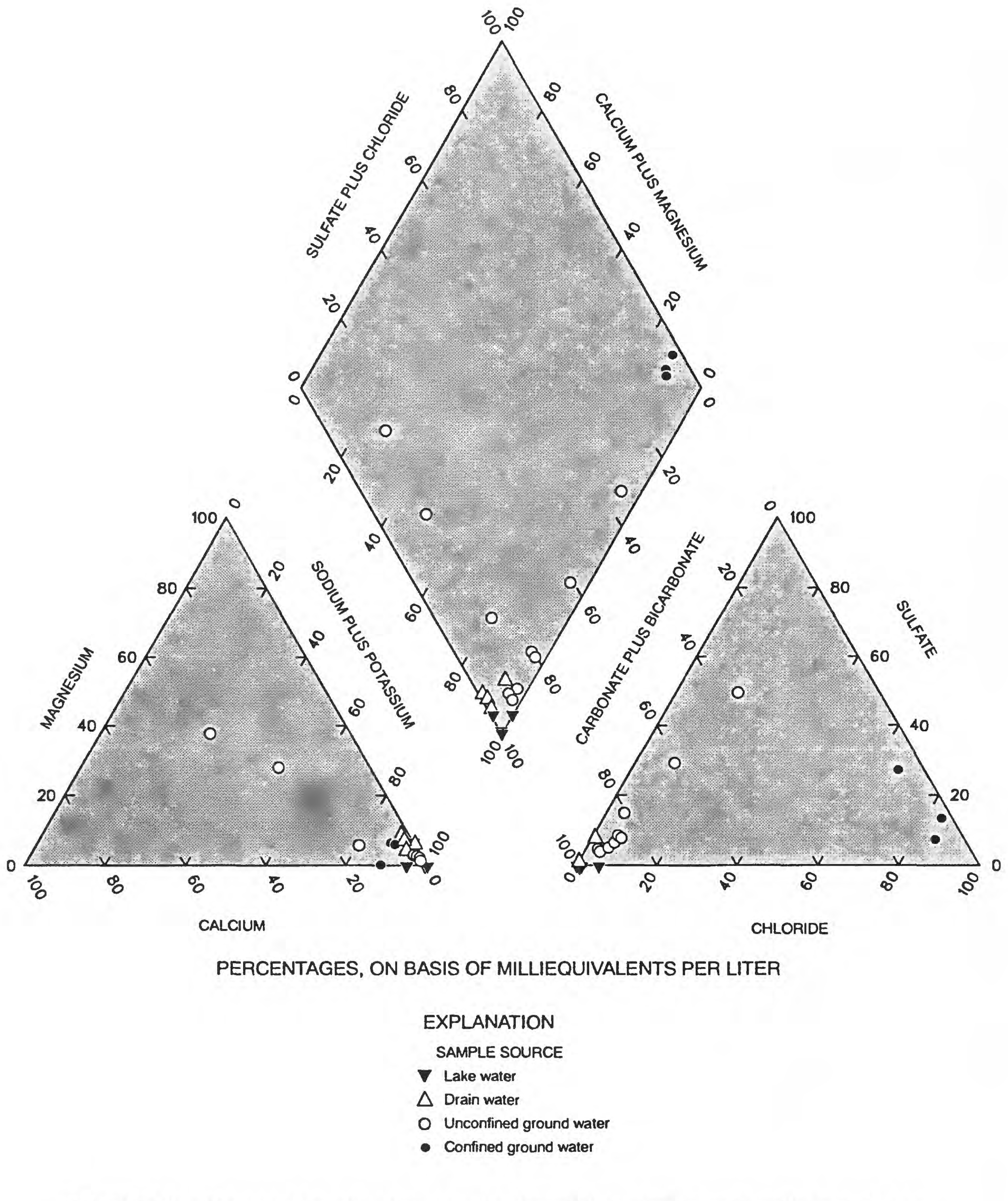

FIGURE 12. --Composition of water samples from lakes, drains, and wells in and near Fernley Wildlife Management Area.

Unconfined Ground Water

Water from the shallow aquifer ranged from a dilute (dissolved solids, 335 mg/L) to a slightly saline (dissolved solids, 2,230 mg/L) Na-HCO_3 type. One sample, from well FWA-2B, was a dilute (dissolved solids, 335 mg/L) Mg-Ca-Na-HCO_3 type. The pH of samples from the shallow aquifer ranged from 7.6 to 8.8, and temperatures ranged from 12 to 17.5°C. Dissolved oxygen was below saturation (6-83 percent) and ranged from 0.5 to 7.0 mg/L. Of the constituents of concern, only arsenic and boron exceeded beneficial-use criteria (table 3).

The composition of ground water from well FWA-5 (fig. 5) appears to be influenced by seepage from sewage ponds to the northwest of the well. Most major ions are at higher concentrations in this water than in water from other wells to the south of A-Drain. The higher concentrations of dissolved organic carbon, chloride, and dissolved solids--along with higher alkalinity and lower dissolved-oxygen concentrations and Eh values--indicate sewage-influenced ground water.

Confined Ground Water

Water samples obtained from the confined aquifer ranged from a slightly saline (dissolved solids, 2,170 mg/L) to a very saline (dissolved solids, 16,500 mg/L) Na-Cl type. Dissolved-oxygen concentrations generally were low, ranging from 0.4 to 1.0 mg/L (4-11 percent saturation), and pH ranged from 6.9 to 7.9. Ground-water temperatures ranged from 12°C at shallow flowing wells on the playa to 88°C at Fernley Hot Spring. Constituents of concern were present in substantial concentrations in water from the confined aquifer (table 3).

Stable Isotopes

Stable isotope ratios of hydrogen ($^2H/^1H$) and oxygen ($^{18}O/^{16}O$) in ground-water samples from the Fernley basin indicate that the water has been slightly to moderately affected by evaporation. Two general sources of water can be identified by their stable isotopic composition (fig. 13), the Truckee Canal and precipitation in the Truckee Range. Water from the Truckee Canal (δD, -97; $\delta^{18}O$, -12.6) is the major source for ground-water recharge in the southern part of the basin. Well FWA-2A (fig. 5) contains the most evaporated water in the basin as a result of sprinkler application of Truckee Canal water to alfalfa fields near the well. All other ground water in the southern part of the basin sampled for this study is a mixture of Truckee Canal water and evaporated Truckee Canal water. Figure 13 is a graph showing δD as related to $\delta^{18}O$ and indicates that the isotopic composition of other ground-water samples is intermediate between those of Truckee Canal water and FWA-2A water composition. The slope of this evaporation-mixing line is about 4.5 and is typical of values for water undergoing evaporation (Fontes, 1980, p. 78). Recharge in the Truckee Range provides water for the confined aquifer along the western side of the basin. Wells FWA-7 and 8 (figs. 5 and 13) are completed in this aquifer, and water from them is isotopically lighter than water recharged by the Truckee Canal. The isotopic composition of a water sample from the Fernley Hot Spring was similar to water from the confined aquifer (fig. 13).

Stable isotope (34/32) composition of sulfur in ground-water samples from the southern part of the Fernley basin is near zero and is probably derived from oxidation of reduced sulfur minerals (pyrite and others) found in volcanic rocks of the area (Schoen and Rye, 1970). A water sample from well FWA-8 (fig. 5) had a $\delta^{34}S$ value of 15.7 permil and is typical of water undergoing sulfate reduction. Pearson and Rightmire (1980, p. 254) state that ^{34}S tends to be enriched in the sulfate phase because ^{32}S is preferentially incorporated into the sulfide phases. Hydrogen sulfide is present in ground water from well FWA-8 as is a black precipitate (FeS) on the aquifer material (well FWA-7 has similar properties).

Ground water from the southern part of the Fernley basin has a stable carbon (13/12) isotopic ratio ranging from -12.1 to -15.8 permil for inorganic carbon. The Truckee Canal, which is the source of this ground water, had a $\delta^{13}C$ of -9.6 permil. The $\delta^{13}C$ range of the ground water is typical of values produced by oxidation (decomposition) of soil-organic matter to HCO_3^- or CO_2 produced by plant-root respiration.

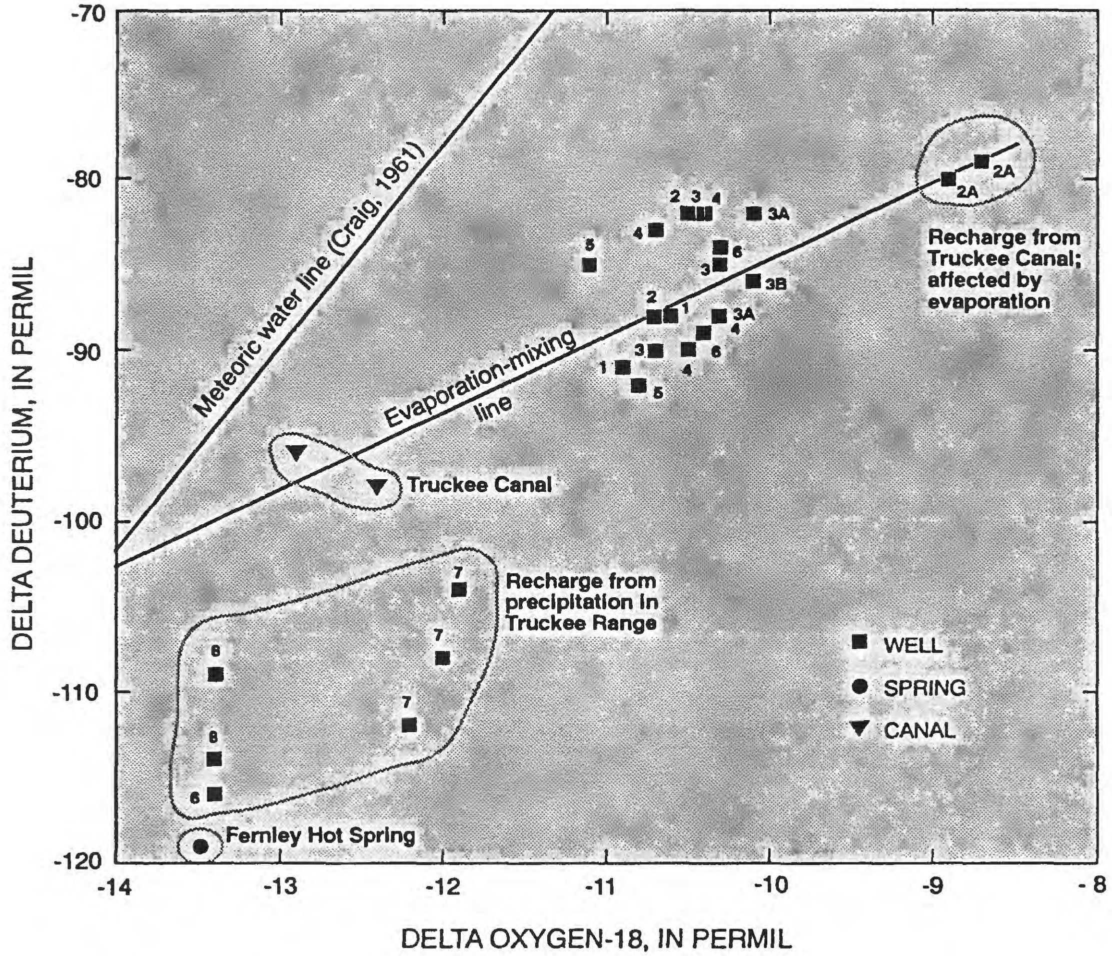

FIGURE 13.--Relation between stable isotopes of hydrogen and oxygen for water samples collected from wells, Fernley Hot Spring, and Truckee Canal in and near Fernley Wildlife Management Area. Well numbers represent sites shown in figure 5.

SEDIMENT COMPOSITION

Sediment samples were collected from drain and lake bottoms (herein referred to subsequently as "bottom sediment") in Stillwater and Fernley WMA's. Specifically, samples were collected from TJ and Paiute Diversion Drains, D-Line Canal, and South Lead Lake in Stillwater WMA, and from A-Drain and South Pond in Fernley WMA. In addition, unconsolidated sediment (referred to as "Pleistocene lake sediment") from augered sampling wells was collected from each well opposite the screened interval. Details of sample-collection procedures and analyses are described by Hoffman and others (1990).

Hoffman and others (1990) provided results of bottom-sediment analyses from 20 sites in and near Stillwater WMA where they found arsenic, lithium, mercury, and molybdenum to equal or exceed the maximum baseline range of concentrations given by Shacklette and Boerngen (1984) for soils of the western United States. Results of chemical analyses of bottom sediment and Pleistocene lake sediment are summarized in table 5 and all analyses were reported by Rowe and others (1991). Most of the bottom-sediment samples were dark, fine grained, anaerobic muds at the time of sampling. Lithologic logs, including descriptions of material penetrated during augering of shallow ground-water sampling wells, were also reported by Rowe and others (1991, p. 173-176). In general, the unconsolidated Pleistocene lake sediment from these wells was light brown to olive-gray clayey sand and silt with some mottling, indicating localized reducing zones, probably associated with detrital organic matter (Rowe and others, 1991, p. 173-176).

Sediment Chemistry

All sediment samples collected for this study were analyzed for 44 elements by standard whole-rock dissolution and inductively coupled plasma analysis (Harms and others, 1990). In addition, the reactive fraction (surface coatings and some easily dissolved minerals) of 16 bottom-sediment and Pleistocene-lake sediment samples from wells was analyzed for 10 elements by partial-solution techniques (table 6). This extraction method involved heating the sediment samples with hot hydrochloric acid and analyzing the resulting solution for trace elements of interest. This extraction is operationally defined and is designed to break down all components of the sediment except the most resistant silicates and aluminosilicates (Horowitz, 1985, p. 46).

Results of chemical analyses of sediments for this study show that the sediment composition from Stillwater and Fernley WMA's is typical of surficial soil from the Carson River basin, except for an enrichment in arsenic, boron, mercury, lithium, molybdenum, and uranium. Figure 14 shows the relation between trace elements in samples from this study and those from the Carson River basin study (Tidball and others, 1991). Median values for arsenic, boron, mercury, lithium, molybdenum, selenium, and uranium in bottom-sediment samples were higher for this study than those for the Carson River basin study and correspond with those cited by Hoffman and others (1990) that exceeded baseline values and, thus, were elements of concern at Stillwater WMA. The apparent enrichment in trace elements may be due to the location of the Carson Desert, specifically the Carson Sink, because it is the terminus for the Carson River, where sediment has been deposited for many thousands of years. Because the Carson Desert is a closed basin, it retains all the dissolved constituents transported in by the Carson River (except some removed by winds), thus creating a mechanism whereby certain trace elements can become concentrated.

TABLE 5.--*Statistical summary of selected trace-element concentrations in lake and drain bottom sediment and Pleistocene lake sediment collected from Stillwater and Fernley Wildlife Management Areas and vicinity. For each three-line data group, upper number (in parentheses) is median concentration, middle numbers are minimum and maximum concentrations, and lower number (in parentheses) is number of samples analyzed*

[All concentrations expressed in milligrams per kilogram. Abbreviation and symbol: NC, median value not calculated because all values were less than analytical reporting level (2.0 milligrams per kilogram); <, less than]

Type of sediment	Arsenic	Boron	Chromium	Copper	Lead	Lithium	Manganese	Mercury	Molybdenum	Selenium	Uranium	Vanadium	Zinc
Carson River Basin Study[1]													
	10	6.1	29	26	16	37	630	0.02	2.0	0.3	3.3	88.5	66
Stillwater Wildlife Management Area and Vicinity[2]													
Lake bottom	(16) 8.8-35 (21)	(26) 11-104 (18)	(33) 25-100 (21)	(37) 22-67 (21)	(18) 15-46 (21)	(75) 25-190 (21)	(700) 530-1,200 (21)	(0.48) 0.04-18 (21)	(4.0) <2.0-9.0 (21)	(0.40) <0.1-1.2 (21)	(9.0) 4.8-22 (18)	(100) 67-190 (21)	(83) 57-96 (21)
Drain bottom	(21) 7.8-120 (22)	(17) 5.6-60 (19)	(36) 22-85 (22)	(33) 19-400 (22)	(20) 15-190 (22)	(52) 31-94 (22)	(665) 430-1,400 (22)	(0.23) 0.04-14 (22)	(3.0) <2.0-73 (22)	(0.55) <0.1-8.3 (22)	(6.8) 5.1-57 (22)	(94) 54-310 (22)	(75) 41-160 (22)
Lake, Pleistocene	(17) 1.8-240 (19)	(46) 8.0-99 (14)	(31) 2.0-132 (19)	(42) 11-64 (19)	(19) 13-23 (19)	(110) 32-149 (19)	(720) 400-1,500 (19)	(0.04) <0.02-0.28 (19)	(3.0) <2.0-33 (19)	(0.20) <0.1-0.70 (19)	(4.5) 0.26-6.9 (18)	(120) 17-190 (19)	(87) 42-100 (19)
Fernley Wildlife Management Area and Vicinity[2]													
Lake bottom	(40) 20-47 (6)	(59) 40-390 (5)	(33) 20-43 (6)	(37) 25-49 (6)	(14) 11-17 (6)	(52) 27-220 (6)	(880) 590-1,000 (6)	(0.04) <0.02-0.06 (6)	(24) 5.0-44 (6)	(1.3) 0.60-5.0 (6)	(5.7) 2.5-21 (6)	(125) 89-140 (6)	(68) 52-87 (6)
Drain bottom	(49) 42-58 (4)	(16) 15-16 (2)	(36) 35-36 (2)	(34) 33-34 (2)	(16) 16-17 (2)	(26) 26-27 (2)	(690) 690-690 (2)	(0.09) 0.06-0.12 (2)	(5.0) 5.0-5.0 (2)	(5.4) 4.6-6.0 (4)	(3.9) 3.4-4.6 (4)	(110) 110-110 (2)	(76) 75-77 (2)
Lake, Pleistocene	(17) 6.9-28 (10)	(2.8) 0.80-5.6 (10)	(32) 24-58 (10)	(28) 19-47 (10)	(12) 8-13 (10)	(34) 22-47 (10)	(815) 600-1,200 (10)	(0.04) <0.02-0.10 (10)	(NC) <2.0-<2.0 (10)	(0.08) <0.1-0.20 (10)	(1.3) 0.85-2.3 (10)	(110) 95-210 (10)	(78) 61-97 (10)

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[1] Median values for soil samples from the Carson River basin (Tidball and others, 1991).

[2] Summarized from data reported by Hoffman and others (1990) and Rowe and others (1991).

TABLE 6.--*Chemical analyses of total-recoverable fraction*[1] *of core material and bottom sediment from wells, lakes, and drains in and near Stillwater and Fernley Wildlife Management Areas*

[Chemical analyses expressed in milligrams per kilogram, except as indicated for iron. Abbreviations: FWA, Fernley Wildlife Management Area; LLAH, Lead Lake auger hole; g/kg, grams per kilogram; <, less than]

Site (figs. 3, 5)	Date	Arsenic	Boron	Chromium	Iron (g/kg)	Lead	Lithium	Manganese	Mercury	Molybdenum	Selenium
					Stillwater Wildlife Management Area						
LLAH-1	11-29-88	17	120	20	15	<100	80	680	0.03	<5.0	<1
LLAH-2	11-29-88	13	150	20	15	<100	70	530	.04	2.9	<1
LLAH-3	11-30-88	12	60	20	8.5	<100	60	730	.04	<5.0	<1
LLAH-4	11-30-88	22	160	20	14	<100	110	500	.06	<6.0	<1
LLAH-5	11-30-88	7	60	10	10	<100	30	260	.02	<1.0	<1
TJ Drain	01-12-89	19	100	20	13	<100	20	450	.15	29	<1
Paiute Drain	01-12-89	18	50	30	16	<100	40	890	.88	<6.0	<1
D-Line Canal	01-12-89	8	30	10	9.0	<100	20	260	.16	2.9	<1
Lead Lake	01-12-89	23	140	20	18	<100	40	420	4.5	<12	<1
					Fernley Wildlife Management Area						
FWA-2A	09-06-88	11	10	10	7.9	<100	10	270	0.02	<1.0	<1
FWA-3A	09-07-88	24	30	20	18	<100	20	960	.06	<5.0	<1
FWA-3	09-08-88	15	20	10	7.1	<100	10	380	.04	<4.0	<1
FWA-4	09-08-88	13	20	10	13	<100	10	420	.05	<4.0	<1
FWA-5	09-08-88	21	40	20	17	<100	30	870	.06	<5.0	<1
A-Drain	01-20-89	44	30	10	12	<100	10	330	.05	5.2	1
South Pond	01-20-89	22	90	20	12	<100	20	600	.03	4.1	2

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[1] "Total-recoverable" is the amount of a given constituent that is in solution after a bottom-sediment sample has been extracted or digested by a method that results in dissolution of readily soluble substances. Complete dissolution of all particulate matter is not achieved by the extraction or digestion treatment employed and there is reason to suspect that the determination actually represents something less than the "total" amount (95 percent) of the constituent sought in both phases of the sample.

Arsenic concentrations ranged from 2.8 to 140 mg/kg for the less-than-2-mm (whole sample) and 1.8 to 240 mg/kg for the less-than-62-µm (fine fraction) size fractions. Median arsenic concentrations were 17 mg/kg for the whole sample and 25 mg/kg for the fine fraction. Figure 15 shows the distribution of arsenic in Pleistocene lake sediment and bottom sediment. Arsenic is present primarily in surface coatings on mineral grains, as shown in figure 15 (approximately 85 percent of arsenic is in surface coatings). This agrees with the conclusions from a study south of Fallon (Lico and others, 1987). Grains with visible surface coatings contained the greatest amount of arsenic, whereas the mineral grains themselves contained low concentrations. The oxygenated environment in the Pleistocene lake sediment is conducive to the formation of ferric (oxy)hydroxides (FeOOH) that coat the surface of grains and adsorb arsenic and other trace elements. In contrast, bottom sediment from drains and lakes that are in reducing environments contains about 60 percent of arsenic in surface coatings (fig. 15). In this sediment, iron is present as Fe^{2+} and is much more soluble than in the oxygenated environment in the Pleistocene lake sediment. In the drain and lake sediment, iron sulfide solubility controls Fe^{2+} concentrations. Iron sulfide is not known to be an efficient adsorber of arsenic. Even though the percentage of arsenic in surface coatings is less in the drain and lake sediment, the concentration of arsenic is greater (median concentration of 21 mg/kg in surface coatings, compared to 14 mg/kg in surface coatings from oxygenated environment) than that from the Pleistocene lake sediment. This indicates that bottom sediment in lakes and drains is acting as a collector of arsenic.

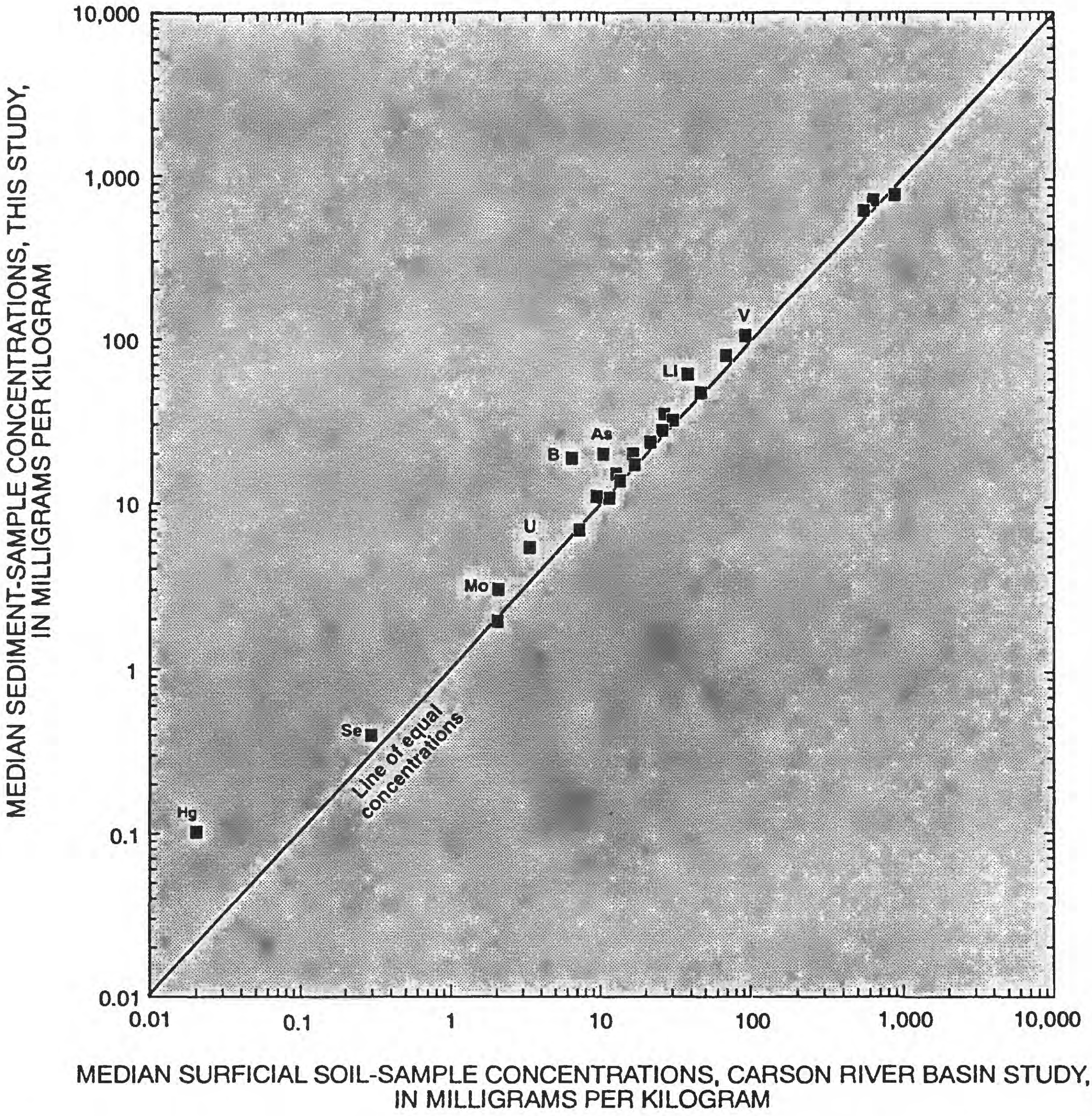

FIGURE 14. --Median concentrations of trace elements associated with sediment samples from drains, lakes, and well cores for this study (Rowe and others, 1991, table 28) compared with median concentrations for surficial soil samples from the Carson River basin study (Tidball and others, 1991). Selected data points that lie away from the line of equal concentrations are as follows: As, arsenic; B, boron; Hg, mercury; Li, lithium; Mo, molybdenum; Se, selenium; U, uranium; V, vanadium.

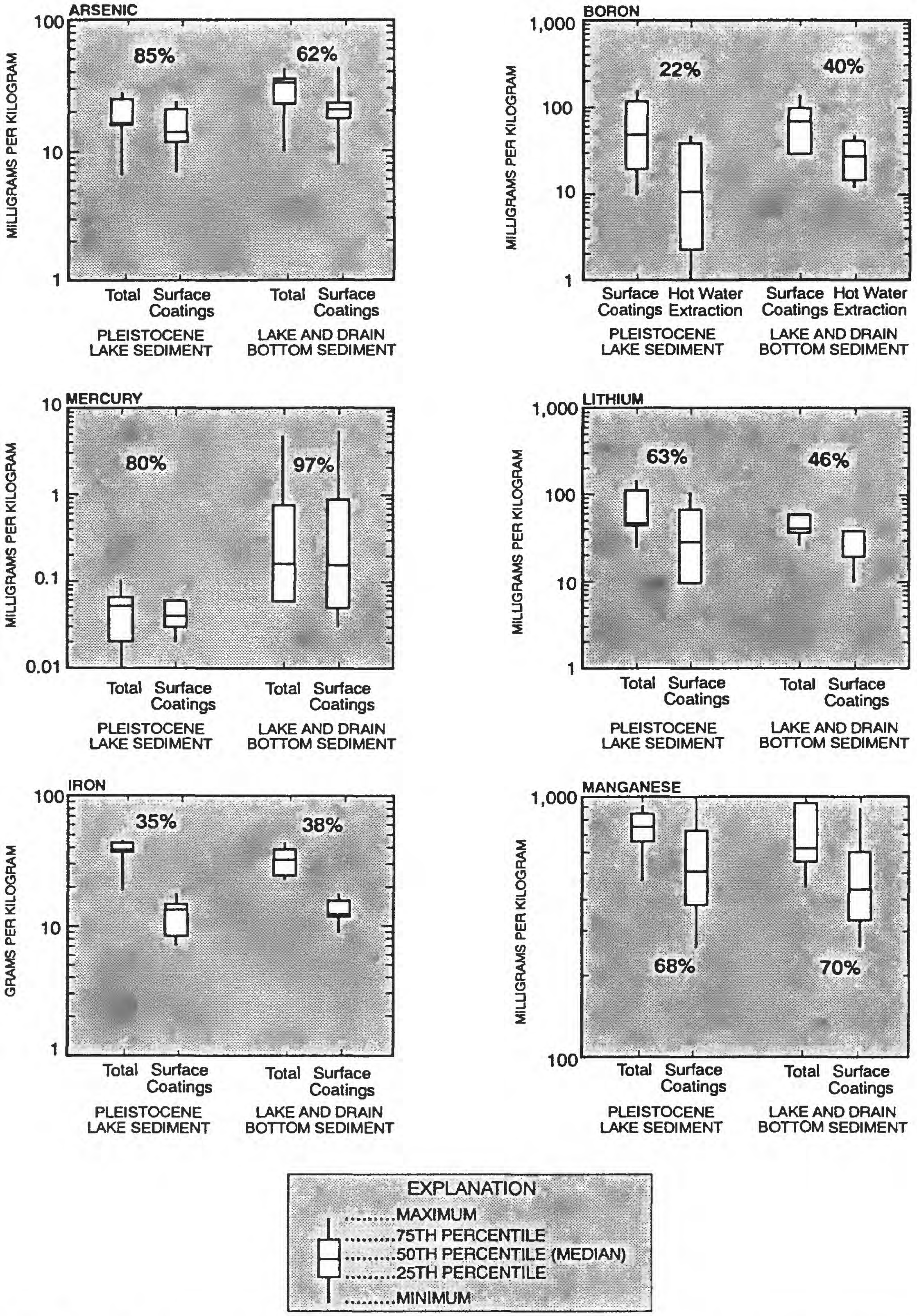

FIGURE 15. --Trace-element concentrations in total sediment and surface-coatings of 10 Pleistocene lake sediment samples and 6 lake- and drain-bottom sediment samples from Stillwater and Fernley Wildlife Management Areas. Percentage above or below boxplots indicates fraction of element contained in surface coatings and other acid-soluble phases.

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Boron concentrations in sediment samples, as determined by hot water extraction methods, ranged from 0.8 to 390 mg/kg and had a median value of 19 mg/kg. The fine-fraction sample (<62 µm) contained much higher boron (median, 46 mg/kg) than did the whole-sediment sample (median, 15 mg/kg). Median boron concentrations in sediment from the Carson Desert (Stillwater WMA) were much higher than those from the Fernley basin (Carson Desert median, 23 mg/kg; Fernley basin median, 4.8 mg/kg), although the highest value (390 mg/kg) was in the Fernley basin. Boron was more concentrated in lake sediment than in drain sediment or Pleistocene lake sediment, probably due to evaporative effects concentrating boron in lake water. Median boron concentrations in sediment samples from this study (19 mg/kg) were higher than those found in the surficial soil samples of the Carson River basin (6.1 mg/kg; fig. 14) by Tidball and others (1991), probably because lake sediment (relatively high boron concentrations) included in the data set increased the observed median value.

Ten Pleistocene lake and six drain and lake bottom-sediment samples were analyzed for boron using a strong-acid digestion that dissolves most surface coatings but not the mineral grains themselves. When compared with the results of the hot water extraction method, the values of the acid-digestion method were high (fig. 15). The hot water extraction of Pleistocene lake sediment recovered only about 22 percent of the boron recovered by the strong-acid digestion, indicating the boron is in a form other than water-soluble boron salts. In samples from drains and lakes, only about 40 percent of the boron recovered by the strong-acid digestion was recovered by the hot-water extraction. These results indicate that a larger fraction of boron in lakes and drains may be available to the biota than that in Pleistocene lake sediment.

Concentrations of mercury in bottom sediment and Pleistocene lake sediment from Stillwater and Fernley WMA's ranged from less than 0.02 to 18 mg/kg, and the median value was 0.10 mg/kg. Hoffman and others (1990) reported extremely high mercury in Carson Lake and Stillwater Slough bottom sediment (14 and 18 mg/kg, respectively), and their data are included in this report (table 5). 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 sediments are present over a large part of the Carson Desert, which is the terminus of the Carson River. The source of the contamination was verified by comparing the median mercury concentrations from the Carson Desert (0.18 mg/kg) to those from the Fernley basin (0.04 mg/kg). The Carson River does not flow into the Fernley basin and no known large-scale mills that used mercury operated there, so the condition of the sediment in the Fernley basin probably represents that of the Carson Desert prior to contamination. Median mercury concentrations in sediment collected for this study are an order of magnitude greater (fig. 14) than those for soil samples in the entire Carson River basin (Tidball and others, 1991). This may be due in part to the higher mercury concentrations in the bottom-sediment samples that result in a higher median concentration than that for the soil samples. Mercury is concentrated in the coarse fraction (whole-sediment median, 0.12 mg/kg; fine-fraction median, 0.08 mg/kg). Lake and drain bottom-sediment samples had higher median mercury concentrations (lake bottom sediment, 0.32 mg/kg; drain bottom sediment, 0.18 mg/kg) than Pleistocene lake sediment samples (0.04 mg/kg), indicating that drains and lakes are contaminated but that mercury has not been mobilized into the shallow aquifer (Pleistocene lake sediment) due to the relative insolubility of mercury in water. Mercury typically is mobile with sediment in surface water but not in a dissolved state, except possibly as methylated mercury. Virtually all of the mercury in sediment samples analyzed by partial-solution methods for this study is adsorbed mercury on surface coatings or possibly is elemental mercury incorporated in the sediment (fig. 15).

The median lithium concentration for sediment samples collected in this study was 61 mg/kg and the range was 22-220 mg/kg. Lithium was concentrated in the fine fraction (less than 62 µm), and the median concentration was 78 mg/kg. The median value for lithium in the whole sediment was 52 mg/kg. Lithium was highest in lake-bottom sediment (median, 74 mg/kg), next highest in Pleistocene lake sediment (median, 61 mg/kg), and lowest in drain-bottom sediment (median, 49 mg/kg). Lithium concentrations are high in lake-bottom sediment probably because of the evaporative concentration of lake water and subsequent incorporation of lithium into minerals (probably clay minerals). The ground water in Pleistocene lake sediment contains high concentrations of lithium (see "Water quality" section) due to evapotranspirative concentration of solutes which causes lithium to be incorporated into minerals and grain coatings in the unconsolidated sediment. The median lithium concentration in this study (61 mg/kg) was greater than that found in surficial soil samples from the Carson River basin study (37 mg/kg) by Tidball and others (1991). About 63 percent of the lithium in Pleistocene lake sediment is contained in surface coatings, whereas about 46 percent of lithium in drain and lake bottom sediment is in labile surface coatings (fig. 15).

Molybdenum concentrations in sediment samples ranged from less than 2 to 73 mg/kg. The fine-grain fraction of sediment contained most of the molybdenum (median, 5 mg/kg). The highest median concentration (5.5 mg/kg) was in lake-bottom sediment; the median concentration of drain-bottom sediment was 3 mg/kg, and of Pleistocene lake sediment was less than 2 mg/kg. Molybdenum concentrations were slightly higher in samples collected for this study (fig. 14) compared with surficial soil samples from the Carson River basin study (median, 3 and 2 mg/kg, respectively; Tidball and others, 1991). Pleistocene lake sediment samples from the Fernley basin all contained less-than-detectable concentrations of molybdenum (2 mg/kg). Where molybdenum was present in bottom sediment at detectable levels, most of it was associated with surface coatings on the grains.

Selenium concentrations in sediment samples from this study ranged from less than 0.1 to 8.3 mg/kg, and the median value was 0.4 mg/kg. No difference in selenium concentrations between the coarse and fine fractions of sediment was observed (both had median values of 0.4 mg/kg). Lake and drain bottom sediment (median, 0.5 and 0.6 mg/kg, respectively) contained more selenium than that in Pleistocene lake sediment (median, 0.1 mg/kg), indicating that lake and drain sediment is acting as a scavenger of selenium from the water column. The hydrogen sulfide-rich environment and the microbes that live in the sediment probably reduce selenate from the water column to selenite or elemental selenium, thus incorporating it into the sediment phase. Median selenium concentrations (0.4 mg/kg) were slightly higher from this study compared with the median (0.3 mg/kg) found for the Carson River basin (Tidball and others, 1991). Selenium concentrations in sediment samples from wells south of Fallon ranged from less than 0.02 to 0.3 mg/kg, and the median was 0.05 mg/kg, indicating that sediment in lakes and drains is enriched over typical sediment in the Carson Desert (Lico and others, 1986). Results from the strong-acid dissolution method were inconclusive because most samples (14 of 16, or 88 percent) contained selenium at concentrations less than the analytical reporting level (1 mg/kg).

Uranium concentrations in sediment samples ranged from 0.26 to 57 mg/kg, and the median value was 5.6 mg/kg. The fine-grained (less than 62 µm) fraction was slightly enriched (median, 6.4 mg/kg) in uranium over the whole-sediment samples (median, 5.5 mg/kg). Uranium was more concentrated in lake and drain sediments (medians, 7.4 and 6.5 mg/kg, respectively) compared with Pleistocene lake sediment (median, 2.8 mg/kg). The highly reducing environment in the lake and drain sediments causes reduction of U^{6+} to U^{4+}, which is insoluble. Under the conditions present in the oxygenated Pleistocene lake sediment, U^{6+} is the stable species, which remains in the aqueous phase as soluble carbonate complexes. Sediment samples from the Carson Desert had higher uranium concentrations (median, 6.3 mg/kg) than those from the Fernley basin (median, 2.4 mg/kg).

Grain coatings are important in controlling the concentrations of trace elements in water associated with sediment (Davis and Hayes, 1986). Evidence indicates that these grain coatings are important in Stillwater and Fernley WMA's. Strong-acid extraction of sediment samples removed about 36 percent of the iron and 69 percent of the manganese from the sediment (fig. 15), indicating the presence of a significant amount of surface coatings. Examination of the sediment by optical petrography shows that many of the iron-bearing minerals (pyroxene and hornblende) possess hematite (or other oxidized iron phase) rims which could readily sorb trace elements.

Most of the trace elements (arsenic, boron, lithium, and uranium) analyzed were on fine-grained (less than 62 µm) sediment, except for mercury which was associated with the coarse fraction. Other investigators, such as Horowitz (1985), have found similar relations between sediment size and trace-element concentrations. Partitioning of the trace elements in the fine-sized fraction may make them more mobile in the surface-water environment at Stillwater WMA.

In general, concentrations of arsenic, boron, mercury, lithium, molybdenum, selenium, and uranium were higher in all sediment samples from Stillwater and Fernley areas than those in the surficial soil samples from the Carson River basin. Concentrations of trace elements generally were higher in lake and drain bottom sediment than in Pleistocene lake sediment, indicating that lake and drain sediment act as historical integrators of certain trace elements. The electrochemical state (redox) of the sediment environment controls the speciation and, thus, the mobility of trace elements such as arsenic, iron, manganese, molybdenum, selenium, and uranium. In drain and lake sediment, a reducing environment is present and reduces the mobility of arsenic, mercury, molybdenum, selenium, and uranium, preferentially concentrating these elements onto surface coatings of detrital grains. In the Pleistocene lake sediment, dissolved oxygen is present and creates an environment where many trace elements are preferentially partitioned into the aqueous phase, thus increasing their mobility and availability to the biota. Mercury is the only human-introduced trace element that has concentrated in surface-water channels, but it has not migrated into the Pleistocene lake sediment.

Mineralogy of Sediment

The mineralogic composition of unconsolidated Pleistocene lake sediment from ground-water sampling wells in Stillwater and Fernley WMA's was determined by X-ray diffraction and optical petrographic analysis. In addition, the clay mineralogy of bottom sediment from drains and lakes within the WMA's was determined. A complete list of minerals identified was reported by Rowe and others (1991).

Sediment samples from all wells near Lead Lake (fig. 3) showed similar mineralogic composition. All samples consisted of very fine sand and silt. Dominant grains were quartz, plagioclase (mostly oligoclase, andesine, and labradorite), calcite, potassium feldspar, basaltic to andesitic lithic fragments, and biotite, and minor amounts of pyroxene and hornblende. Quartz grains were unaltered, but plagioclase grains showed slight alteration, mostly illitic, sericitic, and rare chloritic alteration. Potassium feldspar grains showed either no alteration or only minor illitic alteration on cleavage surfaces. The groundmass of the volcanic lithic fragments was slightly altered to chlorite. Thin shell (gastropod) fragments were present in all samples and consisted of fine-grained calcite. Some of the shell fragments had been recrystallized to coarser grained calcite. Some samples have calcite growing in optical continuity with the shell material (fig. 11), or euhedral calcite crystals growing into voids, or both. Shells from one sample (from site LLAH-7) had diffuse boundaries that may be related to dissolution of calcite. Biotite grains were strongly altered to chlorite in all samples. The pyroxene and hornblende grains showed minor chloritic alteration, mostly along the edges. Minor amounts of chlorite grains (after mafic grains) were present in some samples. One sample (from site LLAH-1) contained euhedral gypsum crystals that have grown in place in the sediment.

Sediment samples from wells in the Fernley basin were similar in composition and alteration to the samples from the Stillwater WMA wells, supporting the assumption that the geochemical processes from Fernley apply in Stillwater WMA. Major sediment components were quartz, plagioclase (mostly andesine, some labradorite, oligoclase, and bytownite), calcite, basaltic (some andesitic) lithic fragments, sedimentary-rock lithic fragments, biotite, hornblende, and pyroxene. Quartz was unaltered, and plagioclase was mostly unaltered, although some grains showed slight illitic or sericitic alteration. Shell fragments of calcite showed little or no precipitation or dissolution features. Volcanic lithic fragments range from unaltered to slightly altered. In the slightly altered fragments, the groundmass is chloritic, pyroxene and hornblende crystals have hematitic rims, and one sample (from site FWA-2A) had chlorite-filled amygdules. Sedimentary-rock fragments consisted of plagioclase, quartz, micritic calcite, and chalcedony. All biotite grains were strongly altered to chlorite. Hornblende and pyroxene had chloritic edges and one sample (from site FWA-7) had rough edges, indicating possible dissolution. Rare opaque minerals consisted of mostly hematite, but some magnetite and ilmenite were present. The presence of magnetite was confirmed by X-ray diffraction analysis.

Clay minerals identified in drain, lake, and well samples from Stillwater and Fernley WMA's by X-ray diffraction analysis include smectite (montmorillonite), illite, kaolinite, and chlorite. In one sample (from site FWA-8), a mixed-clay layer is present.

HYDROGEOCHEMICAL PROCESSES AFFECTING GROUND-WATER COMPOSITION

The geochemical evolution of the water chemistry was modeled for the Fernley basin and Stillwater WMA. Fernley was selected for simulation of geochemical processes because it is hydrologically less complex than Stillwater WMA. Results of simulations for Fernley were assumed to apply to Stillwater because the areas have similar mineralogy, source water, crop types, irrigation practices, and climate. Mass-balance calculations, as described by Plummer and Back (1980), were used to identify possible geochemical reactions controlling the water chemistry at Stillwater and Fernley WMA's. This approach consists of deducing plausible reactions based on measured changes in dissolved constituents between discrete points along a flow path. These reactions can involve solid, aqueous, or gaseous phases and are solved as a series of simultaneous equations that represent the reactions. Coefficients for these geochemical reactions were calculated using the computer program BALANCE (Parkhurst and others, 1982). The phases for the reactions were selected on the basis of mineralogic information, hydrologic data, isotopic composition of aqueous species, and thermodynamic calculations. Thermodynamic calculations were made using the computer program WATEQ4F (Ball and others, 1987).

Fernley Wildlife Management Area

A ground-water flow path was roughly defined for Fernley WMA by using water-level measurements and then generating contour lines that depict the water table (fig. 5). The direction of flow is at right angles to the water-table contours. The hypothetical flow path is oriented approximately due north from the Truckee Canal through sites FWA-2A, FWA-3A, and FWA-4. Water-sample compositions used in the geochemical mass-balance model are shown in table 7. Water discharges north of FWA-4 to A-Drain and subsequently flows to South Pond. Saturation indices for minerals generated by the WATEQ4F program are listed in table 8. This information and other mineralogic information, physical observation of diagenetic changes, and water-quality data were used to select several mineralogic phases for inclusion in the model. A three-step reaction path was used to simulate the possible reactions in the shallow aquifer. The three steps simulated were: (1) Truckee Canal water to (site) FWA-2A water, (2) FWA-2A water to FWA-3A water, and (3) FWA-3A water to FWA-4 water.

Several assumptions were used in constructing this model, including: (1) water samples were collected along a discrete flow path and represent the chemical evolution of water resulting from geochemical processes, (2) no mixing or dispersion (piston flow) occurs along the flow path, (3) phases chosen for reactions are pure end members, except plagioclase (which was assumed to be of labradorite composition, $Na_{0.5}Ca_{0.5}Al_{1.5}Si_3O_8$), and (4) increase in Cl^- down the flow path was from evapotranspiration only. The mass-balance approach assumes congruent dissolution and precipitation, thus incongruent dissolution cannot be directly modeled although it probably takes place. The derived model is not a unique solution for the data set but does represent a set of reactions that are consistent with available aqueous- and solid-phase data and thermodynamic calculations and, as such, is considered a qualitative estimate of processes affecting the chemistry of water in the aquifer.

As water from the Truckee Canal infiltrates into the shallow aquifer, the oxygenated water reacts with minerals in the aquifer changing the dissolved-solids concentration from about 140 mg/L to about 390 mg/L. To account for this increase in dissolved solids, dissolution of plagioclase feldspar, calcite ($CaCO_3$), and a small amount of pyrite (FeS_2) and chlorite ($Mg_5Al_2Si_3O_{10}(OH)_8$), and oxidation of sedimentary organic matter (CH_2O), occurs. Precipitation of montmorillonite ($Ca_{0.17}Al_{2.33}Si_{3.67}O_{10}(OH)_2$) removes mass from the aqueous phase. Exchange of calcium for sodium and potassium on clay minerals, or other minerals with cation-exchange sites, is an important source of sodium and potassium and is a sink for calcium. Potassium feldspar dissolution is another possible source of potassium in this part of the aquifer. These processes can be represented by equation 1 (in millimoles per liter):

$$\begin{aligned}\text{Truckee Canal water} &+ 1.7\ \text{plagioclase} + 0.77\ \text{calcite} + 0.85\ \text{Na-exchange}\\ &+ 0.91\ \text{K-exchange} + 2.1\ CH_2O + 0.06\ \text{chlorite} + 0.02\ \text{pyrite}\\ &= \text{FWA-2A water} + 1.1\ \text{Ca-montmorillonite} + 0.88\ \text{Ca-exchange.}\end{aligned} \qquad (1)$$

TABLE 7.--*Chemical analyses of water samples from Fernley and Stillwater Wildlife Mangement Areas and vicinity*

[Concentrations are expressed in milligrams per liter, except as indicated for aluminum; µg/L, micrograms per liter.]

Sampling site (figs. 3, 5)	Sample date	Calcium	Magnesium	Sodium	Potassium	Bicar-bonate	Car-bonate	Sulfate	Chloride	Silica	Aluminum (µg/L)
					Fernley Wildlife Management Area and vicinity						
Truckee Canal	6-16-89	12	3.9	12	2.5	62	<1	10	8.8	19	10
FWA-2A	6-20-89	23	16	75	30	352	<1	20	13	48	<10
FWA-3A	6-20-89	2.4	1.5	220	13	520	24	19	13	34	<10
FWA-4	6-21-89	2.5	2.3	230	14	522	<1	72	17	35	20
FWA-5	6-21-89	10	15	760	34	783	<1	830	180	34	10
FWA-6	6-20-89	7.1	4.6	250	27	490	<1	180	33	40	<10
FWA-7	6-21-89	170	100	2,500	17	234	<1	930	4,100	39	<20
FWA-8	6-21-89	42	32	840	60	181	<1	160	1,300	36	50
					Stillwater Wildlife Management Area						
LLAH-1	6-14-89	330	860	7,900	370	1,220	<1	9,800	9,300	54	40
LLAH-2	6-14-89	460	700	6,400	180	1,070	<1	7,100	7,500	52	40
LLAH-3	6-14-89	520	290	2,300	81	366	<1	4,100	2,400	58	10
LLAH-4	6-14-89	490	960	8,400	250	1,200	<1	11,000	8,900	42	30
LLAH-5	6-15-89	620	1,200	8,500	200	1,420	<1	12,000	10,000	42	20
LLAH-6	6-15-89	600	1,700	29,000	1,300	398	<1	26,000	35,000	24	80
LLAH-7	6-15-89	250	670	11,000	330	1,630	<1	16,000	8,500	33	50
LLAH-8	6-15-89	610	1,400	24,000	770	664	<1	21,000	31,000	62	50

This reaction is typical of CO_2-charged water reacting with feldspar-rich rocks, producing clay minerals. These types of weathering reactions typically are incongruent; thus the transfer of mass through the aqueous phase is somewhat less than depicted by equation 1. The model accurately predicted the isotopic composition ($\delta^{13}C$ and $\delta^{34}S$) of dissolved bicarbonate and sulfate, thus serving as a check to the model's feasibility. Not included in the model values, and the probable source for arsenic and many other potentially toxic trace elements, is the microcrystalline groundmass that comprises the bulk of the volcanic-lithic fragments present in the sediment. In a previous study, lithic fragments from the Fallon area were found to contain a higher concentration of arsenic (about 30 mg/kg) than whole sediment, quartz, or feldspar (Lico and others, 1986). Alteration of larger grains (feldspar and pyroxene) is visible in thin section and implies that finer grained material (for example, the matrix of volcanic-lithic fragments) also is dissolving, thus releasing elements to the aqueous phase. The relative changes of selected trace elements as ground water evolves down the flow system near Fernley WMA are shown in figure 16. The curves in figure 16 show the ratio of trace-element concentrations to chloride concentrations; this approach is used to mask the concentrative effects of evapotranspiration (and it assumes that no chloride is added to the ground water by dissolution of aquifer material). Concentrations of all plotted constituents except for iron were higher in water from well FWA-2A than those from the Truckee Canal. This indicates that dissolution of aquifer materials is contributing arsenic, boron, molybdenum, uranium, and vanadium to the ground water, while iron is being removed, probably by precipitation of FeOOH.

TABLE 8.--*Saturation indices for selected minerals in ground-water samples from sites in and near Fernley Wildlife Management Area, as calculated using the computer program WATEQ4F (Ball and others, 1987)*

[--, data not available]

Sampling site (fig.5):	Truckee Canal	FWA-2A	FWA-3A	FWA-4	FWA-5	FWA-6	FWA-7	FWA-8
Sampling date:	6-16-89	6-20-89	6-20-89	6-21-89	6-21-89	6-20-89	6-21-89	6-21-89
Mineral (composition)	Saturation index[1]							
Quartz (SiO_2)	0.58	1.0	0.86	0.94	0.95	0.98	1.0	1.0
Chalcedony (SiO_2)	.13	.53	.36	.41	.42	.46	.48	.46
Silica glass (SiO_2)	-.41	.021	-.14	-.096	-.091	-.054	-.031	-.051
Anorthite ($CaAl_2Si_2O_8$)	-4.2	-4.1	-4.7	-3.6	-4.2	-4.4	-4.1	-2.7
Albite ($NaAlSi_3O_8$)	-2.1	-.48	-.11	.61	.61	.057	.66	1.2
Potassium feldspar ($KAlSi_3O_8$)	-.41	1.6	1.1	1.9	1.8	1.5	.95	2.5
Calcite ($CaCO_3$)	-1.1	-.012	.096	-.11	.063	-.014	.13	-.22
Gypsum ($CaSO_4 \cdot 2H_2O$)	-3.1	-2.7	-3.8	-3.2	-1.9	-2.4	-.89	-1.9
Chlorite ($Mg_5Al_2Si_3O_{10}(OH)_8$)	-7.7	-3.0	.085	.014	-.96	-2.1	-2.2	-1.1
Kaolinite ($Al_2Si_2O_5(OH)_4$)	-44	2.0	.42	2.1	1.9	1.4	1.8	3.5
Calcium-montmorillonite ($Ca_{0.17}Al_{2.33}Si_{3.67}O_{10}(OH)_2$)	1.8	2.2	.28	2.2	1.9	1.4	2.0	3.9
Illite ($K_{0.6}Mg_{0.25}Al_{2.3}Si_{3.5}O_{10}(OH)_2$)	.87	2.1	.68	2.5	2.2	1.6	1.6	4.0
Hematite (Fe_2O_3)	9.4	--	--	15	--	14	17	17
Potassium-mica ($KAl_3Si_3O_{10}(OH)_2$)	6.5	8.4	6.7	9.1	8.7	7.9	7.7	11

[1] Saturation index = $\log \frac{[\text{Activity Product}]}{K_T}$;

where K_T = equilibrium constant at temperature T.

By convention, a positive value indicates a mineral can precipitate from solution, and a negative value indicates a mineral can dissolve if present.

As ground water moves down the flow path from well FWA-2A to well FWA-3A, concentrations of dissolved solids increase about 1.5-fold, from about 390 mg/L to about 600 mg/l. Dissolution of plagioclase feldspar and sedimentary organic matter increases the dissolved components in the ground water. Formation of montmorillonite and silica (SiO_2) removes solutes from the ground water. Cation exchange of calcium, magnesium, and potassium for sodium is important in controlling the concentrations of these ions in the water. Equation 2 summarizes these processes for this step in the ground-water model (in millimoles per liter).

$$\begin{aligned} &\text{FWA-2A water} + 1.9 \text{ plagioclase} + 1.5\ CH_2O + 3.3 \text{ Na-exchange} \\ &= \text{FWA-3A water} + 1.2 \text{ Ca-montmorillonite} + 0.42\ SiO_2 \\ &+ 1.1 \text{ Ca-exchange} + 0.40 \text{ Mg-exchange} + 0.29 \text{ K-exchange.} \end{aligned} \tag{2}$$

Gypsum ($CaSO_4 \cdot 2H_2O$) and pyroxene ($CaMg_{0.4}Fe_{1.6}Si_2O_6$) probably are involved in dissolution or precipitation in this part of the aquifer, but the mass transfer attributed to them is very small. Concentrations of the trace elements arsenic, boron, iron, molybdenum, and vanadium (fig. 16) increased at a rate greater than that caused by evapotranspiration, indicating dissolution or desorption of trace-element-bearing phases.

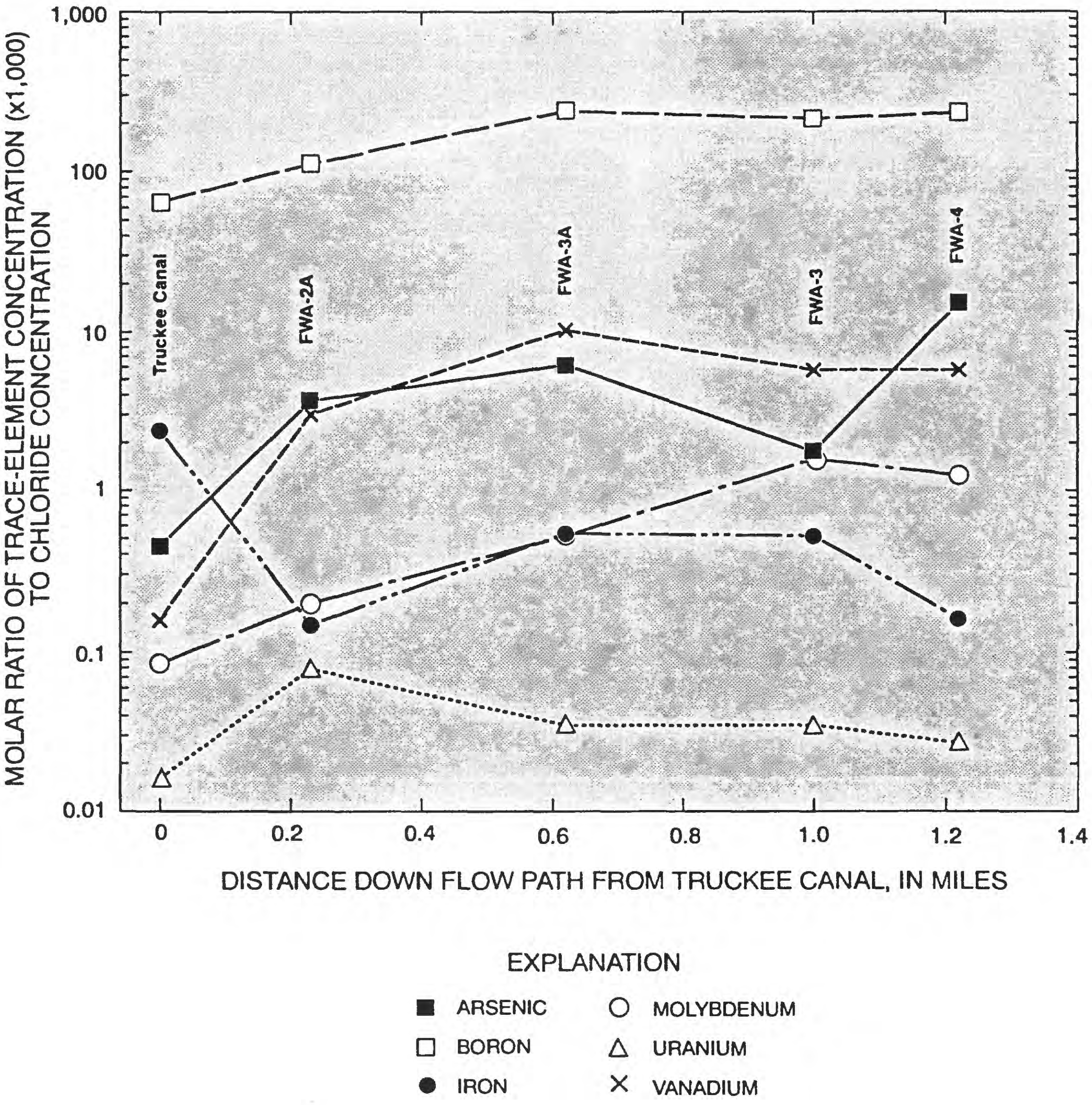

FIGURE 16. --Relation between trace-element concentrations, chloride concentrations, and distance down flow path for water from Truckee Canal and water from wells in and near Fernley Wildlife Management Area. Well locations (FWA-2A - FWA-4) are shown in figure 5.

The final step for the model describing the evolution of ground-water quality in the southern part of the Fernley basin involved the changes in water and mineral composition between wells FWA-3A and FWA-4 (fig. 5). Basically, the same processes were taking place in the final step as in the previous steps, except that sedimentary organic carbon (concentration is less than 0.05 percent in sediment from FWA-4) is not contributing a significant amount of carbon to the reaction. Gypsum also is being dissolved in the aquifer. Small amounts of silica (SiO_2) and illite ($K_{0.6}Mg_{0.25}Al_{2.3}Si_{3.5}O_{10}(OH)_2$) are precipitated in the aquifer. Another important difference in this step is the precipitation of salts in the unsaturated zone. These salts remove substantial amounts of calcium, carbon, and sodium from the aqueous phase. The water table is close to land surface (3 to 6 ft below) where capillary action brings water to the surface and evaporation precipitates calcite ($CaCO_3$) and thenardite (Na_2SO_4). These two minerals were identified in efflorescent salts collected from the Carson Desert; they most likely comprise the majority of the abundant efflorescent salts in this part of the Fernley basin. The active processes in this part of the aquifer can be represented by equation 3 (in millimoles per liter).

$$\begin{aligned}&\textbf{FWA-3A water} + \textbf{0.95 gypsum} + \textbf{0.14 plagioclase}\\ &\quad = \textbf{FWA-4 water} + \textbf{0.025 Ca-montmorillonite} + \textbf{0.068 illite}\\ &\qquad + \textbf{0.11 } \mathbf{SiO_2} + \textbf{1.0 calcite} + \textbf{0.69 thenardite.}\end{aligned} \tag{3}$$

Boron, molybdenum, uranium, and vanadium appear to have reached an equilibrium state in supply and removal processes. Figure 16 shows that most trace-element concentrations remained nearly constant when the effects of evapotranspiration were removed. The major process acting to concentrate solutes in ground water in this part of the flow path is evapotranspiration. Factors causing high evapotranspiration are the shallow water table, abundant phreatophytes, high air temperature, and wind.

The above discussion of processes controlling major- and trace-element compositions is consistent with observed and calculated information from both solid and aqueous phases. The processes discussed are not the only solution to the observations; other processes may be taking place that were not considered in this model.

The ground water in the southern part of the Fernley basin is not in electrochemical equilibrium with respect to arsenic and iron species. Figure 17 is a graph showing Eh (as calculated from various redox couples and platinum-electrode measurements) in relation to pH. Eh values calculated from arsenate-arsenite concentrations fell along the boundary between $HAsO_4^{2-}$ and H_3AsO_3 stability fields, indicating equilibrium exists among arsenic species. Ferric-ferrous iron concentrations in these water samples also appear to be in equilibrium because the calculated Eh values fell along the boundary between $Fe(OH)_3$ and Fe^{2+} stability fields for a total iron concentration of 10^{-9} mol/L. The measured concentrations of total iron are mostly near 10^{-8} mol/L. In contrast, the Eh values from platinum-electrode measurements do not indicate that equilibrium exists. In the Fernley basin, measured (by platinum electrode) Eh values apparently cannot be used for geochemical purposes, such as determining species distributions, mineral saturation indices, or other characteristics. The measured value may represent a mixed potential that consists of several redox couples and also indicates that arsenic or iron do not control the measured potential at the electrode surface. Measured potentials and Eh values calculated using measured species commonly are in poor agreement (Welch and others, 1988; Holm and Curtiss, 1989).

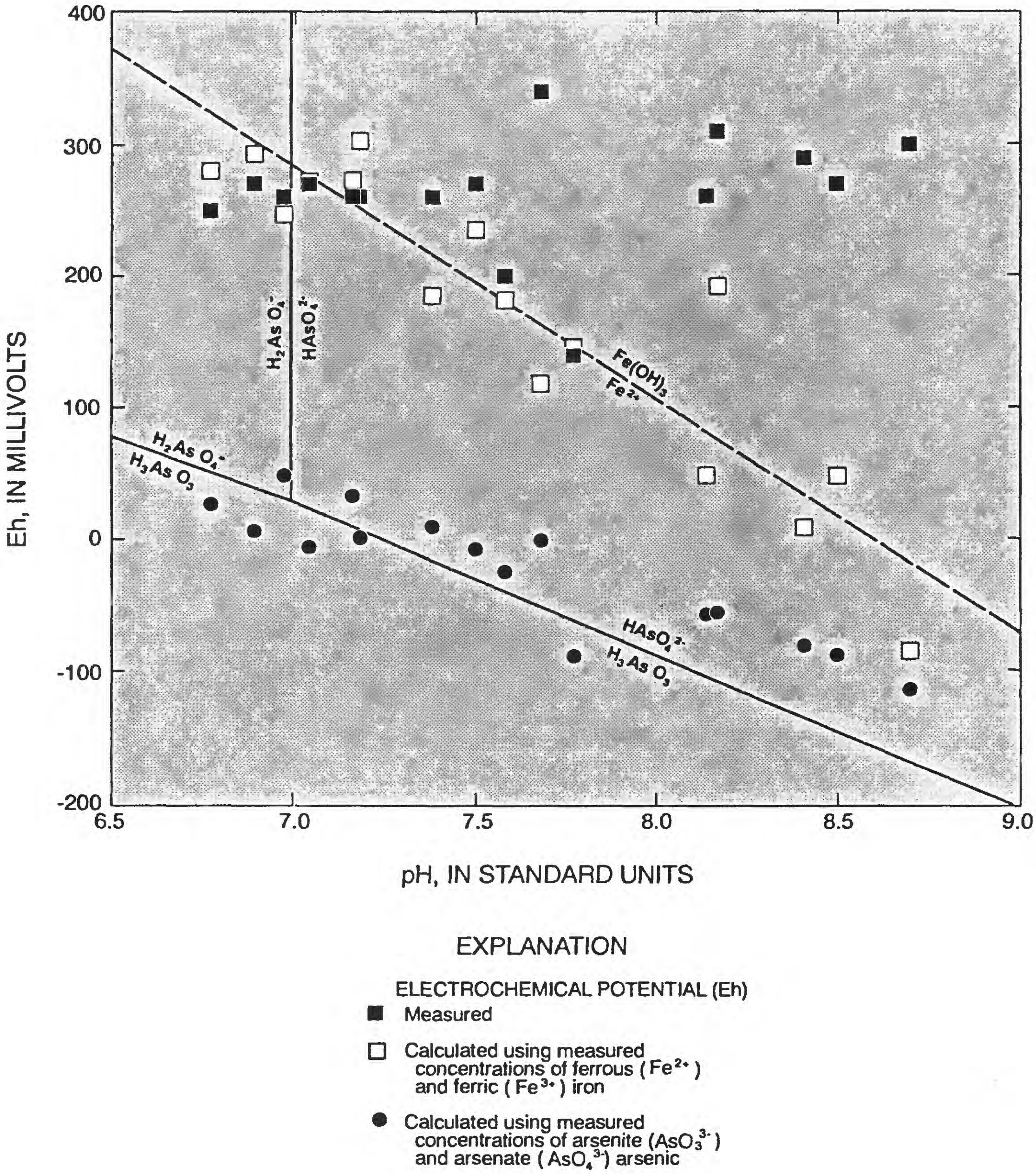

FIGURE 17. --Relation between Eh and pH in ground-water samples from aquifers in and near Stillwater and Fernley Wildlife Management Areas. Stability fields for arsenic (solid lines) and iron (dashed line) are from Welch and others (1988) and Hem (1985), respectively. Iron stability fields were calculated for a total iron concentration of 10^{-9} moles per liter Fe.

Stillwater Wildlife Management Area

Although a ground-water flow path was well defined in the Fernley WMA, no flow path was delineated near Lead Lake in Stillwater WMA. The complex hydrology in Stillwater WMA, controlled by water levels in nearby lakes and drains, prohibited delineation of a flow path that could be modeled. The following discussion, therefore, is a qualitative simulation of processes controlling ground-water chemistry based on observed features (in thin sections), thermodynamic calculations, and processes transferred from the Fernley WMA model.

Major-element chemistry and hydrologic relations suggest that three types of ground water exist: (1) very saline (dissolved solids near 11,000 mg/L) water that is affected by recharge from Paiute Diversion Drain, (2) very saline (dissolved-solids concentration of about 32,000 mg/L) water near the western side of Lead Lake, and (3) briny (dissolved solids concentration near 89,000 mg/L) water present along the northern and eastern sides of Lead Lake. For the purposes of this discussion, qualitative changes will be described assuming type-1 water is the least evolved and type 3 is the most highly evolved type. Representative chemical analyses of ground-water samples from near Lead Lake are listed in table 7.

As ground water evolves from type 1 to type 2, evaporation appears to be the dominant process affecting the composition. Figure 18 shows ratios of major-element concentrations to chloride concentration, plotted against chloride. The curves show that most major elements are concentrated at the same rate as chloride (assumed to be a conservative ion) and suggest that no major chemical reactions are occurring. The exception to this generalization is Ca^{2+}. Examination of thin sections of sediment from wells in this part of the aquifer showed that calcite is precipitating, mostly as crystal overgrowths in optical continuity with calcite shell fragments (fig. 11). Thermodynamic calculations (table 9) indicate oversaturation of the aqueous phase with respect to calcite; thus, precipitation can occur. Carbon (HCO_3^-) remains relatively constant; thus, in order for calcite to be precipitating, CO_2 or organic carbon must be reacting to form HCO_3^- in the shallow ground water. Sulfate concentrations possibly are being reduced by precipitation of gypsum (identified by X-ray diffraction and in thin section of type-2 water), as seen in figure 19. Gypsum precipitation may also be a sink for calcium. Calculated saturation indices (table 9) indicate that gypsum is near equilibrium in most type 1 and 2 water. Another process that could be lowering SO_4^{2-} concentrations is sulfate reduction. Hydrogen sulfide, however, was not detected in the shallow ground water; thus, sulfate reduction probably is minor if it is occurring. Exchange of Ca^{2+} for Na^+ on clay minerals probably can be dismissed as a cause for decreased Ca^{2+} concentrations because there is no concomitant rise in Na^+ concentrations observed in the aqueous phase.

Trace-element concentrations vary widely in type-2 water but generally show no trend as water evolves from type 1 to type 2. Evaporative concentration appears to be the major process affecting trace-element concentrations. The variation in the conservative trace elements (boron and lithium), which is much less than the other elements (arsenic, iron, molybdenum, uranium, and vanadium), indicates that some localized processes may be acting on the nonconservative elements.

As the shallow ground water evolves from type-2 water to type-3 water, major-element concentrations decrease relative to chloride, except for sodium and potassium. The apparent decrease in these elements (Ca, Mg, HCO_3^-, and SO_4^{2-}) may be due in part to the dissolution of sodium chloride and potassium chloride that have accumulated as efflorescent salts by precipitation (rain or snowfall) infiltrating to the shallow ground water. Smith and Drever (1976) documented this process for a similar closed basin in Nevada. These salts are soluble and would thus be the most likely ones to dissolve with the limited amount of atmospheric precipitation that falls in the Lead Lake area.

Calcium concentration is reduced by chemical precipitation of calcite and possibly gypsum. Saturation indices for both calcite and gypsum (table 9) show that a state of oversaturation is present with respect to both minerals; thus, it is possible for these minerals to precipitate thermodynamically. Thin sections prepared from sediment within this part of the aquifer contained calcite, but gypsum was not found.

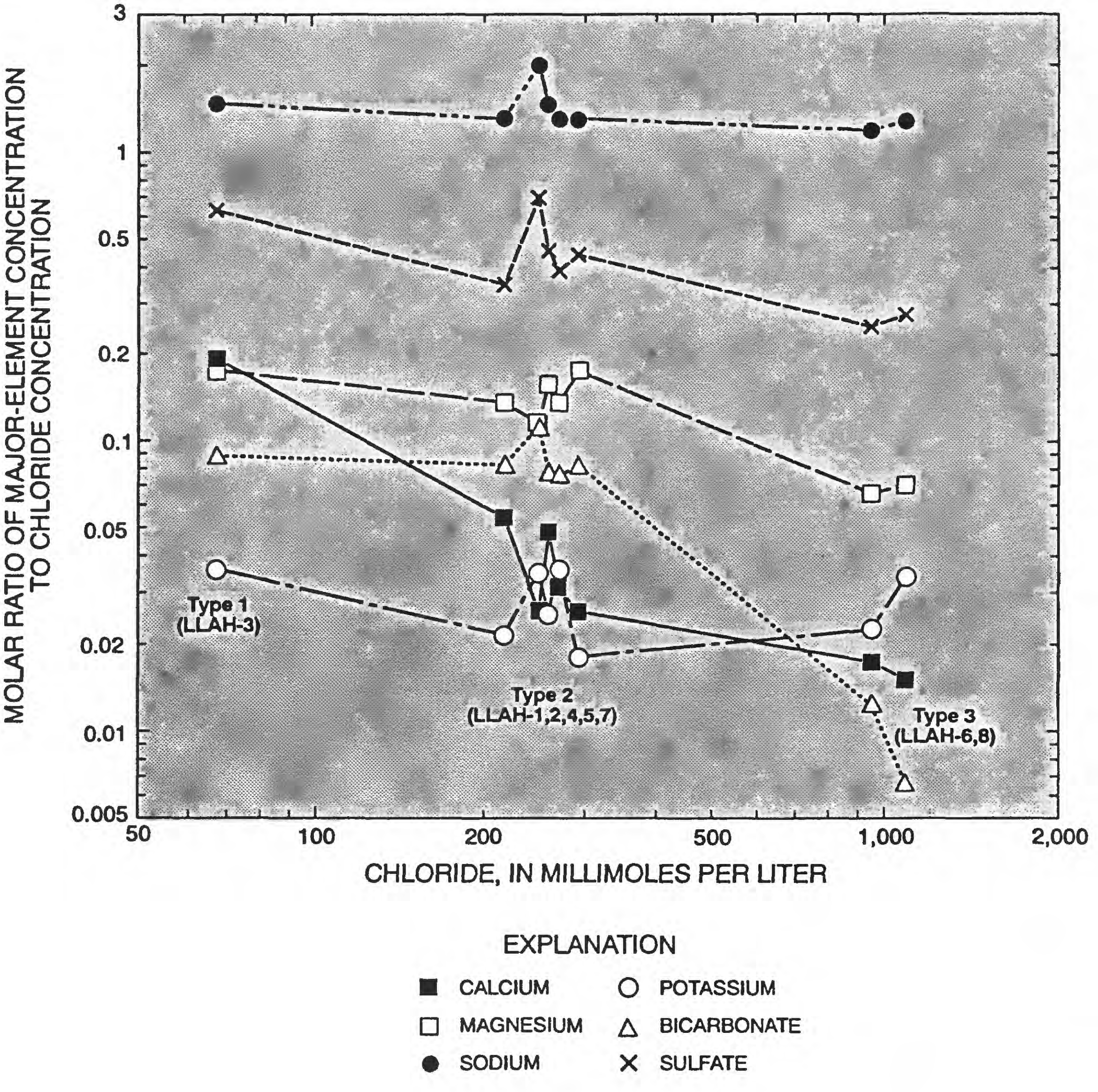

FIGURE 18. --Relation between major-element and chloride concentrations for water from wells near Lead Lake in Stillwater Wildlife Management Area. Water types 1-3 are discussed in text. Well locations (LLAH-1 - LLAH-8) are shown in figure 3.

FIGURE 19. --Euhedral gypsum crystals from Pleistocene lake sediment in Stillwater Wildlife Management Area. Photomicrograph by Patrick Goldstrand, U.S. Geological Survey, November 1990.

TABLE 9.--*Saturation indices for selected minerals in drain- and ground-water samples from the Lead Lake area in Stillwater Wildlife Management Area, as calculated using the computer program WATEQ4F (Ball and others, 1987)*

Sampling site (fig.5):	TJ Drain	Paiute Diversion Drain	LLAH-1	LLAH-2	LLAH-3	LLAH-4	LLAH-5	LLAH-6	LLAH-7	LLAH-8
Sampling date:	6-12-89	9-13-89	6-14-89	6-14-89	6-14-89	6-14-89	6-15-89	6-15-89	6-15-89	6-15-89
Mineral (composition)	Saturation index[1]									
Quartz (SiO_2)	0.46	-0.19	1.2	1.1	1.1	1.1	1.1	0.99	0.014	1.4
Chalcedony (SiO_2)	.023	-.62	.64	.63	.61	.57	.56	.48	-.51	.85
Silica glass (SiO_2)	-.51	-1.2	.14	.12	.11	.057	.054	-.032	-1.0	.34
Anorthite ($CaAl_2Si_2O_8$)	-1.6	-3.5	-2.4	-3.5	-3.1	-4.1	-3.8	-.80	-4.5	-1.2
Albite ($NaAlSi_3O_8$)	.65	-2.9	2.2	1.5	1.1	1.2	1.3	3.2	-.86	3.6
Potassium feldspar ($KAlSi_3O_8$)	1.2	-1.4	3.3	2.4	2.1	2.1	2.1	4.2	.042	4.4
Calcite ($CaCO_3$)	1.4	1.3	.29	.26	.28	.33	.30	.44	.51	.35
Gypsum ($CaSO_4 \cdot 2H_2O$)	-.84	-2.2	-.14	-.050	.005	.061	.17	.28	-.14	.24
Chlorite ($Mg_5Al_2Si_3O_{10}(OH)_8$)	12	9.3	-.76	-3.7	-2.3	-3.5	-4.3	5.7	-2.7	2.4
Kaolinite ($Al_2Si_2O_5(OH)_4$)	-44	-46	4.3	3.5	3.0	2.9	3.4	4.8	2.0	5.0
Calcium-montmorillonite ($Ca_{0.17}Al_{2.33}Si_{3.67}O_{10}(OH)_2$)	.98	-2.8	4.9	3.9	3.5	3.1	3.7	5.5	.73	6.1
Illite ($K_{0.6}Mg_{0.25}Al_{2.3}Si_{3.5}O_{10}(OH)_2$)	1.9	-1.8	5.0	3.7	3.2	3.1	3.4	6.3	1.2	6.5
Hematite (Fe_2O_3)	16	15	14	15	14	13	16	15	12	14
Potassium-mica ($KAl_3Si_3O_{10}(OH)_2$)	7.3	3.4	12	10	9.8	9.8	10	14	9.0	14

[1] Saturation index = $\log \frac{[\text{Activity Product}]}{K_T}$;

where K_T = equilibrium constant at temperature T.

By convention, a positive value indicates a mineral can precipitate from solution, and a negative value indicates a mineral can dissolve if present.

Trace-element concentrations generally were lower (with respect to chloride) for type-3 water when compared with type-2 water (fig. 20). Conservative elements such as boron and lithium also showed a decrease in concentration relative to chloride, which probably was due to dissolution of a chloride-containing salt (NaCl or KCl). Molybdenum and uranium remain relatively constant with respect to chloride, possibly because of oxidation of uranium-bearing organic matter. Welch and others (1990) suggest that sedimentary organic matter in the Carson Desert contains high concentrations of uranium.

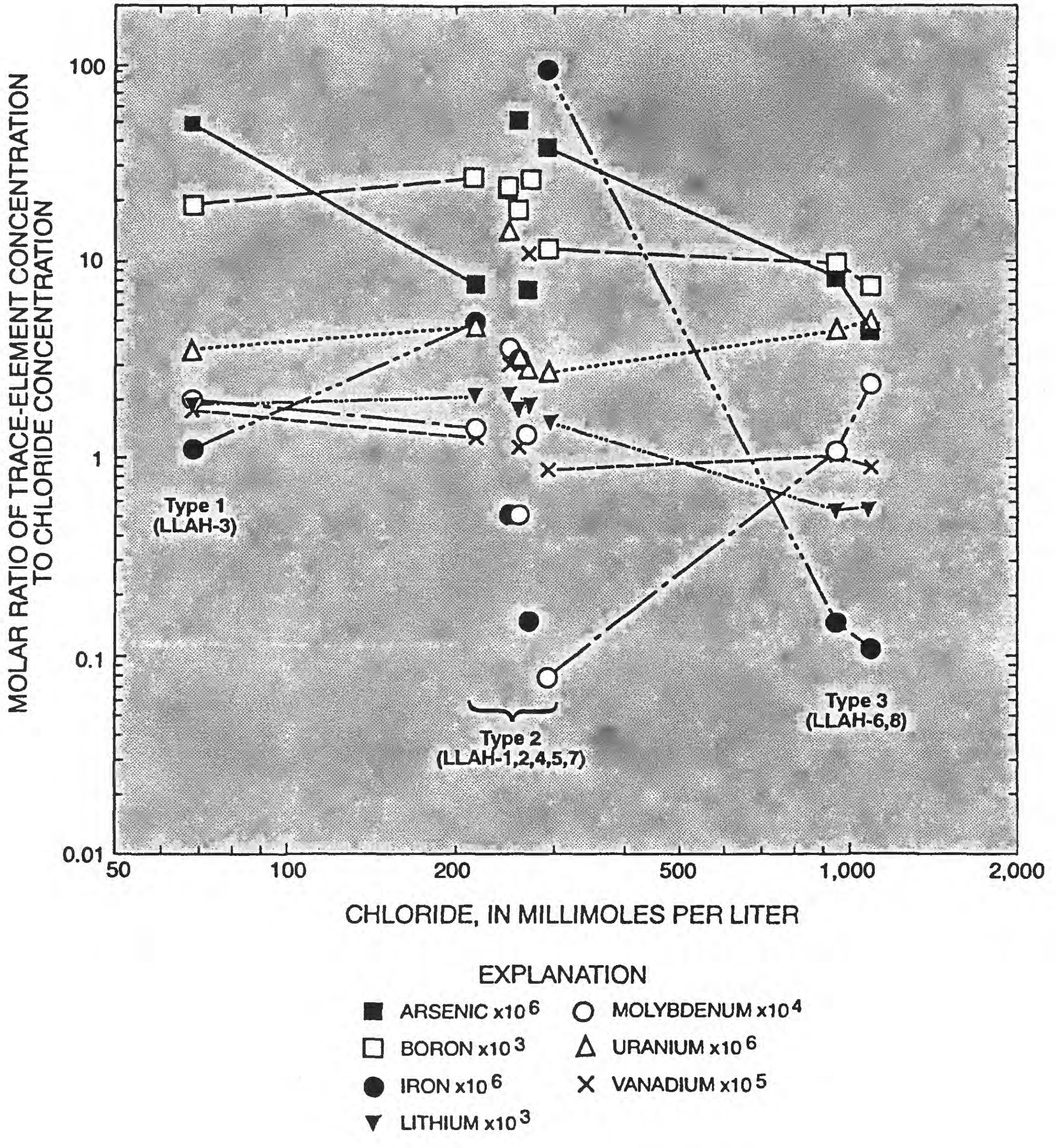

FIGURE 20. --Relation between trace-element and chloride concentrations for water from wells near Lead Lake in Stillwater Wildlife Management Area. Notation in explanation indicates factors by which trace-element concentrations are multiplied to attain ratios of comparable magnitude. Water types are discussed in text. Locations (LLAH-1 - LLAH-8) are shown in figure 3.

HYDROGEOCHEMICAL PROCESSES AFFECTING SURFACE-WATER QUALITY

Fernley Wildlife Management Area

Dissolved constituents are concentrated by evaporation almost two orders of magnitude in surface water flowing into Fernley WMA from between entrance at A-Drain and the Northeast Pond (fig. 5). Figure 21, which shows ratios of major-element to chloride concentrations plotted against chloride, indicates that more than simple evaporative concentration of elements is occurring. Water from the Truckee Canal, the source of most water at Fernley WMA, is applied to agricultural lands on the Fernley bench and recharges the shallow aquifer. Water from the shallow aquifer discharges into a series of drains (fig. 5) serving the agricultural area that coalesce into the A-Drain in the southwestern part of Fernley WMA. The observed increase in concentrations of most elements shown in figure 21 is due to the reaction of this water with minerals present in the shallow aquifer, as discussed in the previous section on "Hydrogeochemical processes affecting ground-water composition." As the water moves downstream from A-Drain to South Pond, then to Northeast Pond, all major elements decreased in concentration relative to chloride, and Ca^{2+} and CO_3^{2-} + HCO_3^- decreased at a faster rate than the others. The rapid decrease in Ca^{2+} and carbonate species is due to the precipitation of calcite in South and Northeast Ponds. This results in calcite coatings on most of the rock surfaces in the ponds. Thermodynamic calculations indicated that the water in A-Drain, South Pond, and Northeast Pond is oversaturated with calcite; thus, calcite can precipitate.

Trace elements in surface water follow the same general trend as the major elements; that is, they decrease in concentration relative to chloride as water flows downstream. All trace elements shown in figure 22 decrease at about the same rate, except for iron, which decreases rapidly from the A-Drain sampling site to South Pond. A reddish precipitate (FeOOH) was observed at South Pond on sediment and rock surfaces, and at times the water was tinted red owing to very fine FeOOH particles suspended in the water column. The processes in Fernley WMA described above pertain to one point in time and, as the water bodies (South and Northeast Ponds) either desiccate or fill up with more dilute water, other processes such as precipitation or dissolution may become important. Also, yearly temperature changes--which affect both chemical and biological processes--probably have a significant effect on the water chemistry.

The fact that all major and trace constituents decrease in concentration relative to chloride may indicate that, besides evaporative concentration, another source of chloride also is present. Chloride-containing salts may be present in the sediment around and beneath the lakes in Fernley WMA and possibly could dissolve and contribute chloride to the lake water. This process is not supported by a concomitant rise in sodium or potassium, which would take place if NaCl or KCl were dissolving, thus this process is considered not likely.

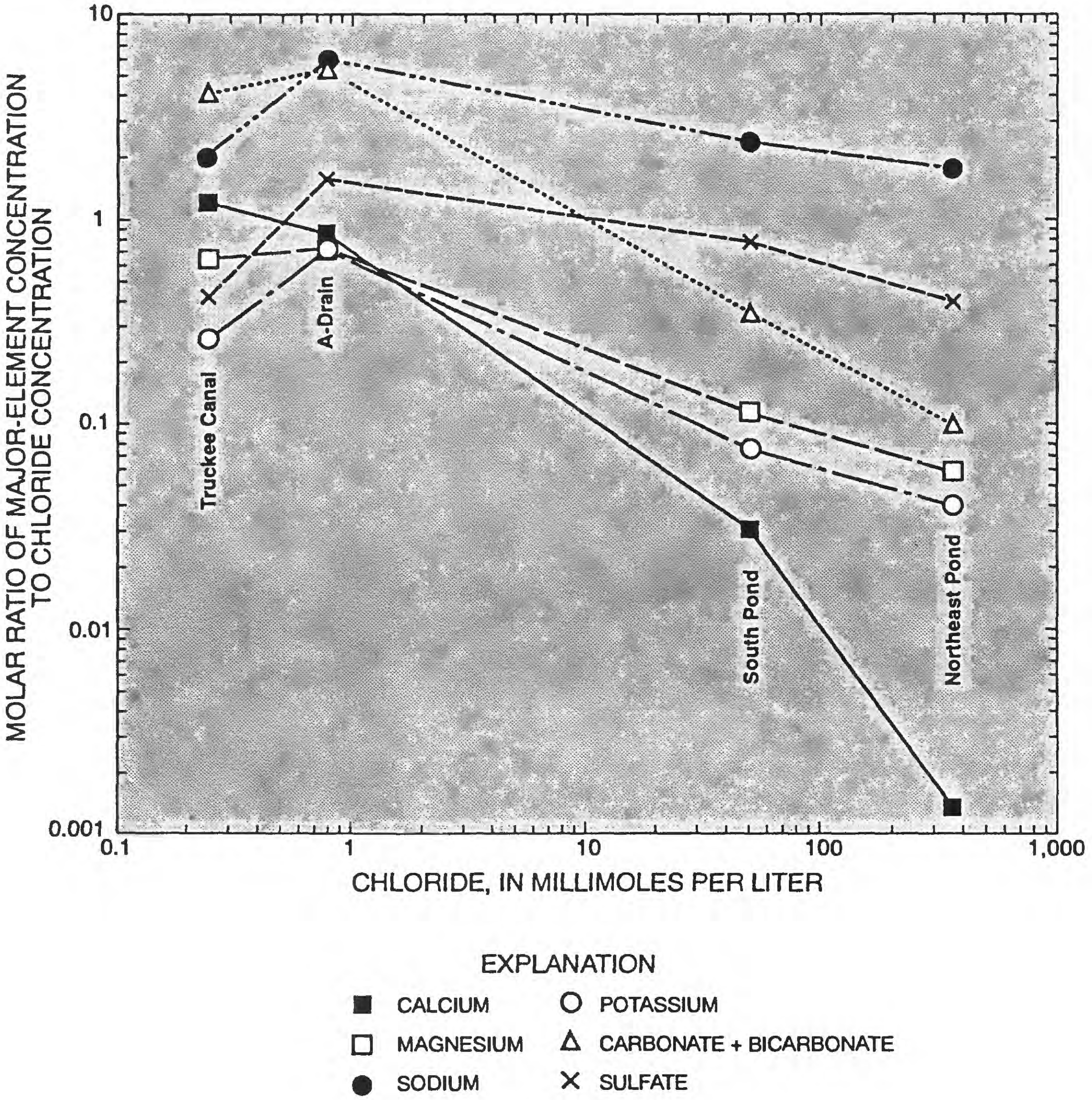

FIGURE 21. --Relation between major-element and chloride concentrations for surface water from sites in and near Fernley Wildlife Management Area. Site locations are shown in figure 5.

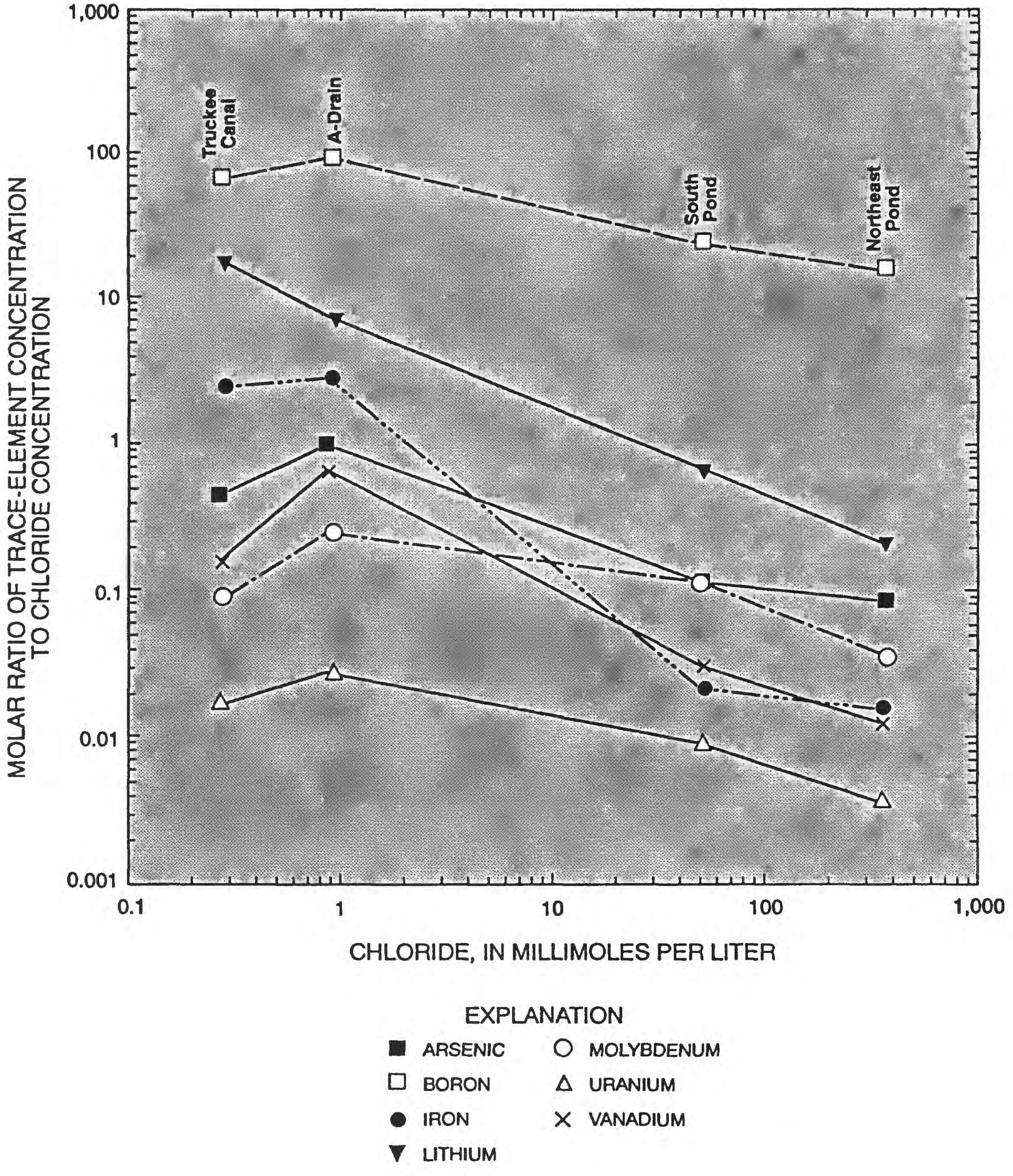

FIGURE 22. --Relation between trace-element and chloride concentrations for surface water from sites in and near Fernley Wildlife Management Area. Site locations are shown in figure 5.

Stillwater Wildlife Management Area

The major contributors of water entering Lead Lake are Paiute Diversion and TJ Drains and the D-Line Canal (see section on "Local hydrology"). Changes in major-element chemistry relative to chloride are shown in figure 23. The most obvious feature depicted in figure 23 is the large decrease in inorganic carbon and calcium relative to chloride for Lead Lake, compared to inflowing water. The water in Lead Lake is oversaturated with calcite, as indicated by thermodynamic calculations. Calcite was identified in sediment samples from Lead Lake by X-ray diffraction analysis. Other major-element concentrations (Mg^{2+}, Na^{+}, K^{+}, and SO_4^{2-}) probably were caused by simple mixing of inflowing water. Apparently, no geochemical processes are removing or adding a significant amount of these major solutes to Lead Lake.

Water samples from TJ and Paiute Diversion Drains and D-Line Canal generally had higher concentrations of trace elements than those from Lead Lake (relative to chloride), which suggests that some process or processes are removing these elements from the aqueous phase in Lead Lake. The concentrations of boron and vanadium can be explained by the simple mixing of inflowing water to Lead Lake (fig. 24). Dissolved arsenic concentrations decreased owing to incorporation of arsenic in coatings on lake-sediment surfaces (as discussed in the section "Sediment chemistry"). Pore fluids from cores collected at Lead Lake had about the same arsenic concentrations as those in the overlying water column (ranges from 31 to 150 µg/L in lake water, and from 110 to 140 µg/L in pore fluids), according to Rowe and others (1991). Eh and pH values suggest that dissolved arsenic should be in the As^{3+} state (as H_3AsO_3). Coprecipitation or combination with sulfide, as discussed by Kobayashi and Lee (1978), appears to be the controlling process keeping arsenic concentrations low in Lead Lake.

Iron is precipitating as amorphous iron sulfide surface coatings on the sediment in Paiute Diversion and TJ Drains and in Lead Lake. The black precipitate is quickly oxidized to a light greenish color upon exposure to air. Hydrogen sulfide was abundant in pore water, and was measured as high as 84 mg/L from a Lead Lake core. The process responsible for hydrogen sulfide production is the bacterial reduction of sulfate, as expressed in the following equation:

$$2CH_2O + SO_4^{2-} = H_2S + 2HCO_3^{-}. \qquad (4)$$

The sulfate concentration drops to near zero at a 3-in. depth in the Lead Lake core. Stable sulfur isotopes also indicate that sulfate reduction was active in the sediment of TJ Drain and Lead Lake (see section on "Stable isotopes"). Eh values near -150 mV are indicative of highly reducing conditions, and with the sulfate essentially absent, methane probably is being produced.

The geochemical environment in the upper few inches of detrital sediment was quite different from that of the lake water. The lake water is commonly saturated with dissolved oxygen and has Eh values near +280 mV. It is at the sediment-water interface where geochemical reactions are changing the composition of the water. As stated in the previous section on sediment chemistry, lake- and drain-bottom sediment act as collectors (or concentrators) of certain trace elements. Molybdenum, uranium, and vanadium are highly soluble in alkaline, oxidizing environments (Hem, 1985) such as the surface water in Lead Lake, but virtually insoluble in more reducing conditions such as those present in the sediment of Lead Lake. Reduced uranium (+4 oxidation state) is readily adsorbed on organic matter (Szalay, 1964), which is abundant in the sediment of Lead Lake (Rowe and others, 1991).

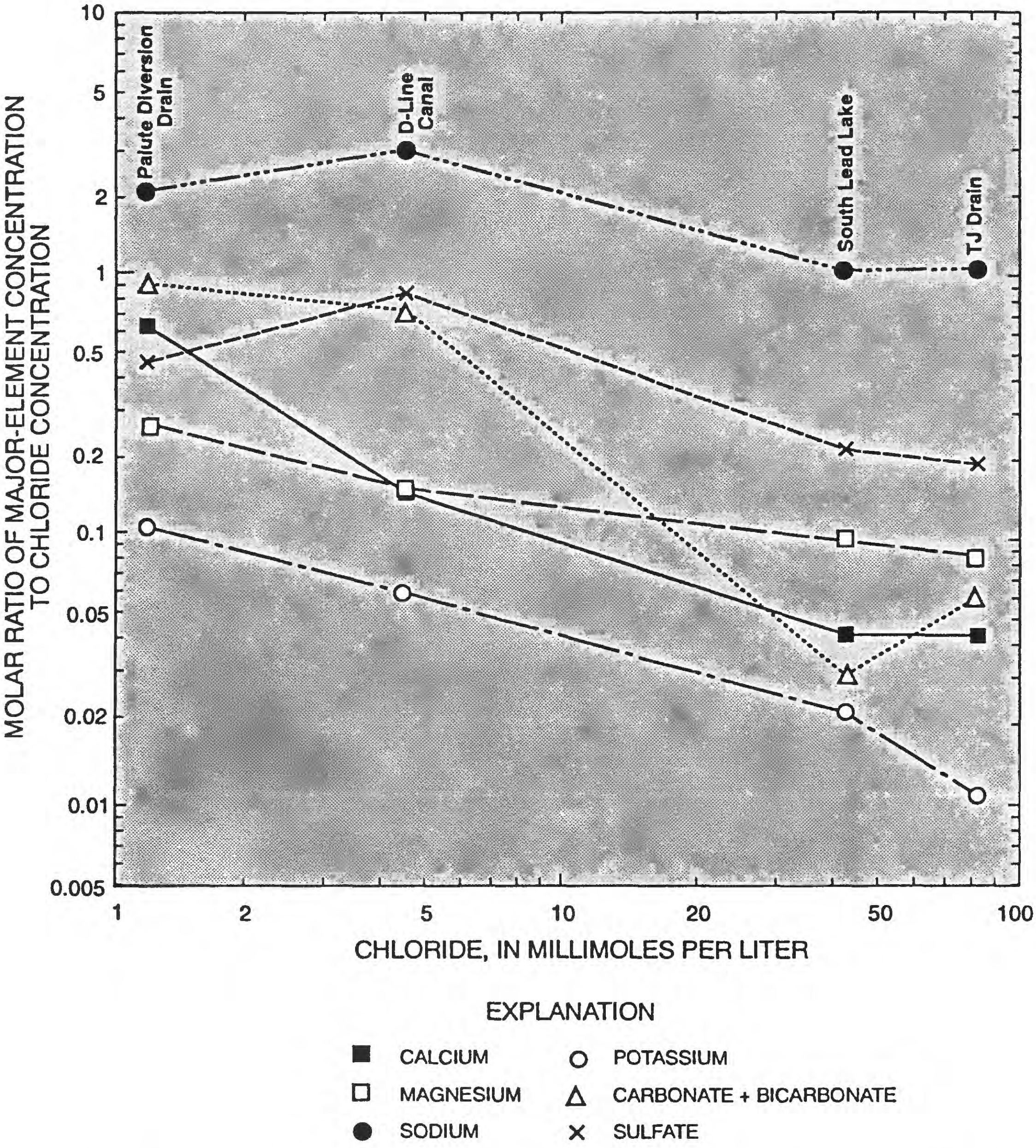

FIGURE 23. –Relation between major-element and chloride concentrations for surface water from sites in Stillwater Wildlife Management Area. Site locations are shown in figure 3.

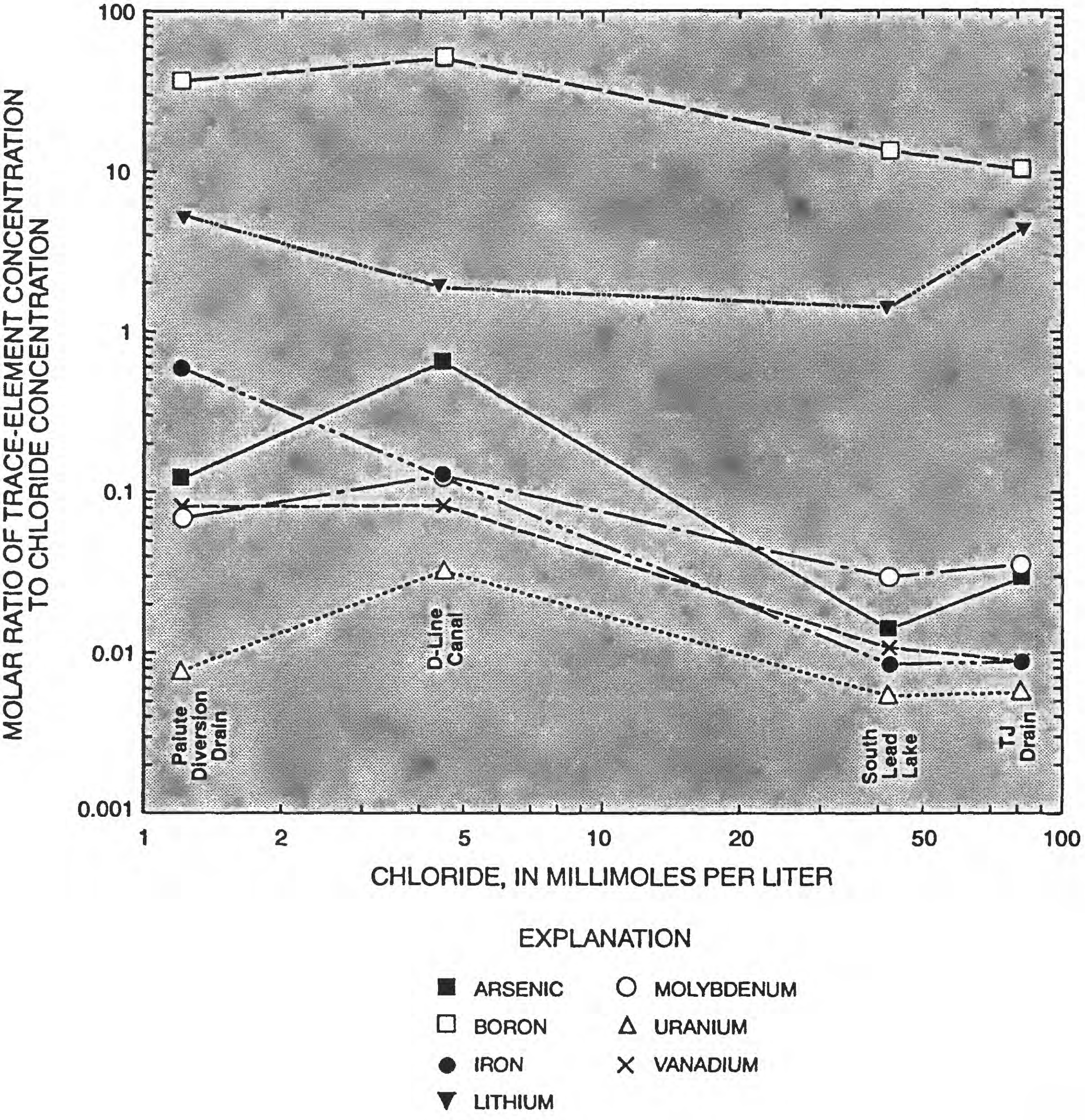

FIGURE 24. --Relation between trace-element and chloride concentrations for surface water from sites in Stillwater Wildlife Management Area. Site locations are shown in figure 3.

SUMMARY

Stillwater Wildlife Management Area receives inflow mainly from irrigation-return flow with minor contributions of water from precautionary reservoir releases and from precipitation. During the study period, 1986-89, western Nevada was experiencing drought conditions. Under those conditions, no freshwater enters the marsh, and the U.S. Fish and Wildlife Service must depend on reduced flows of irrigation drainage to sustain the wetlands. The Fernley Wildlife Management Area receives inflow from irrigation-return flow and seepage from the Truckee Canal.

Inflow to Stillwater WMA is received through six channels--TJ, Paiute Diversion, Hunter, and Stillwater Point Diversion Drains; Stillwater Slough; and the D-Line Canal--which empty into different parts of the Wildlife Management Area. These channels carry water that contains high concentrations of potentially toxic dissolved trace constituents such as arsenic, boron, lithium, molybdenum, un-ionized ammonia, uranium, and vanadium. Water with the highest concentration of potentially toxic constituents is delivered by TJ and Hunter Drains. Large loads of dissolved solids and sodium also are delivered by these channels and are of concern. Stillwater Point Diversion Drain, Stillwater Slough, and TJ Drain contribute the largest part of the dissolved-solids load to Stillwater WMA. Established Federal and State water-quality criteria for the protection of wildlife are commonly exceeded for un-ionized ammonia, arsenic, boron, sodium, and dissolved-solids concentrations in the water entering Stillwater WMA. As water moves through the wetlands, evapotranspiration further concentrates those elements.

Drain water entering Fernley WMA generally is of acceptable quality for aquatic life; arsenic and boron are the only constituents exceeding beneficial-use criteria. Water in the ponds at Fernley WMA is higher in dissolved solids than it is in the drains entering the ponds; the pond water commonly exceeds criteria for arsenic, boron, sodium, dissolved solids, and un-ionized ammonia.

Surface-water composition at both Stillwater and Fernley WMA's is controlled by inflow of local ground water, evaporation, precipitation of calcite and ferrous monosulfide, interaction with pore water in the highly reducing sediment, and sorption of trace elements onto surface coatings of sediment. Precipitation of ferric oxyhydroxide removes iron, and probably many trace elements, from solution in South Pond at Fernley WMA.

Mean daily loads of dissolved solids entering Stillwater WMA were determined from measurements of discharge and specific conductance and relations between specific conductance and dissolved solids. Dissolved-solids loads were calculated at 50 ton/d for Stillwater Point Diversion Drain, 28 ton/d for Stillwater Slough, 24 ton/d for TJ Drain, 10 ton/d for Hunter Drain, 7.6 ton/d for Paiute Diversion Drain, and 3.4 ton/d for the D-Line Canal. In the Fernley WMA, A-Drain delivers about 2.8 ton/d of dissolved solids to South Pond.

Ground water is an important component in the flow of TJ and Hunter Drains. Seepage into these drains from the shallow ground-water aquifer is the major component of base flow which is present all year but dominant during November to March (the nonirrigation period). Ground-water quality in the Stillwater WMA is poor; nearly all samples exceeded criteria for arsenic, boron, sodium, and dissolved solids. Uranium concentrations also are high, as great as 1,500 µg/L. Ground-water flow into Lead Lake is dependent on the water levels in adjacent lakes. Large quantities of water can enter Lead Lake when the lakes to the south (Dutch Bill Lake and Pappis Pond) are full, and create a gradient toward Lead Lake. TJ Drain, with its major ground-water component, also empties into Lead Lake.

Ground water comprises most of the flow into the drains that enter Fernley WMA. The shallow aquifer in the southern part of the Fernley basin generally is of acceptable quality for most constituents but commonly exceeds beneficial-use criteria for arsenic and boron. The confined aquifer contains water that has higher concentrations of dissolved solids than the shallow aquifer and commonly exceeds criteria for arsenic, boron, sodium, and dissolved solids.

The sediment in Lead Lake and in the sampled drains is accumulating trace elements from the overlying water column. Most of the trace elements are either incorporated into or adsorbed onto labile coatings of grain surfaces. In general, concentrations of arsenic, boron, mercury, lithium, molybdenum, selenium, and uranium were elevated in lake and drain bottom sediment compared with the median values for Carson River basin soil.

Sediment in ponds and drains at Fernley WMA are accumulating arsenic, boron, molybdenum, and uranium. Concentrations of these elements were higher in lake and drain bottom sediment than in Pleistocene lake sediment (aquifer material).

Processes controlling the composition of the shallow ground water at Stillwater and Fernley WMA's include evaporation, dissolution of detrital organic matter (by oxidation to HCO_3^-), calcite, and silicates, and precipitation of montmorillonite, calcite, and gypsum. Localized redox conditions and evaporation are responsible for high trace-element concentrations in the ground water. Uranium possibly is released by the oxidation of organic matter in the aquifer.

SUPPLEMENTAL INFORMATION ON WELLS

Data for the 25 wells discussed in this report were collected during the initial part of the detailed study. The site designations used herein are listed in table 10 and cross referenced to the site numbers and well names from the earlier data report by Rowe and others (1991).

TABLE 10.--*Information on wells referred to in this report*

[--, unknown]

Site designation	Site number[1]	Well name	Well depth (feet below land-surface datum)
		Stillwater Wildlife Management Area (figs. 2 and 3)	
AWP	67	Artesian Well near Paiute Drain	--
DBR	71	DeBraga 14-6 Well	--
FAE	70	U.S. Fish and Wildlife Service Well 3	700
FAW	69	U.S. Fish and Wildlife Service Well 2	680
FIR-13	68	Fallon Indian Reservation Well 13	20
LLAH-1	59	Lead Lake Well 1	20
LLAH-2	60	Lead Lake Well 2	18
LLAH-3	61	Lead Lake Well 3	15
LLAH-4	62	Lead Lake Well 4	13
LLAH-5	63	Lead Lake Well 5	14
LLAH-6	64	Lead Lake Well 6	16
LLAH-7	65	Lead Lake Well 7	11.5
LLAH-8	66	Lead Lake Well 8	14
		Fernley Wildlife Management Area (fig. 5)	
FWA-1	72	Well 1	119
FWA-2	73	Well 2	228
FWA-2A	74	Well 2A	60
FWA-2B	75	Well 2B	45
FWA-3	78	Well 3	31
FWA-3A	76	Well 3A	51
FWA-3B	77	Well 3B	35
FWA-4	79	Well 4	14
FWA-5	80	Well 5	15
FWA-6	81	Well 6	16
FWA-7	82	Well 7	14
FWA-8	83	Well 8	13

[1] Sequential numbers for wells assigned by Rowe and others (1991, table 22).

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