HYDROLOGY AND WATER CHEMISTRY OF THE BENTON LAKE BASIN WITH EMPHASIS ON THE FATE OF DISSOLVED SOLIDS AT BENTON LAKE NATIONAL WILDLIFE REFUGE, WEST-CENTRAL MONTANA

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CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (Continued)

TABLES

TABLES--Continued

CONVERSION FACTORS, VERTICAL DATUM, ABBREVIATED UNITS, AND ACRONYMS

Multiply	By	To obtain
acre	4,047	square meter
acre-foot (acre-ft)	1,233	cubic meter
cubic foot per second (ft^3/s)	0.028317	cubic meter per second
foot (ft)	0.3048	meter
inch (in.)	25,400	micrometer (µm)
	25.4	millimeter
	2.54	centimeter (cm)
mile (mi)	1.609	kilometer
mile per hour	1.609	kilometer per hour
pound (lb)	453,600,000	microgram
	453,600	milligram
	453.6	gram (g)
	0.4536	kilogram
pound per cubic inch	27.68	gram per cubic centimeter (g/cm^3)
pound per square foot (lb/ft^2)	0.4882	gram per square centimeter (g/cm^2)
quart	946.4	milliliter (mL)
	0.9464	liter (L)
square mile (mi^2)	2.59	square kilometer
ton (short)	907.2	kilogram

Temperature can be converted from degrees Celsius (°C) to degrees Fahrenheit (°F) by the equation:

$$°F = 9/5\ (°C) + 32$$

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929--A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Water year: A water year is the 12-month period from October 1 through September 30. It is designated by the calendar year in which it ends.

Chemical concentration in water is reported in milligrams per liter (mg/L) or micrograms per liter (μg/L). Milligrams per liter is a unit expressing the solute mass (milligram) per unit volume (liter) of water and is about the same as parts per million unless concentrations are more than 7,000 milligrams per liter (Hem, 1985, p. 55). One thousand micrograms per liter is equivalent to 1 milligram per liter. Tritium concentration is expressed in tritium units (TU). A tritium unit is equal to 3.2 picocuries per liter (pCi/L), which is equal to 2.2 radioactive disintegrations per minute in a unit volume (liter) of water. Chemical concentration of sediment and rocks is reported in micrograms per gram (μg/g), which is equal to parts per million.

Specific conductance of water is a measure of the ability of water and dissolved constituents to conduct an electrical current and is an indication of the ionic strength of the solution. Specific conductance is expressed in microsiemens per centimeter at 25 °C (μS/cm) and increases with the concentration of dissolved constituents.

Additional abbreviations used in this report:

inst	instantaneous
IT	incremental titration
percent	parts per hundred
permil	parts per thousand
PVC	polyvinyl chloride

Acronyms used in this report:

MBMG	Montana Bureau of Mines and Geology
MSCA	Montana Salinity Control Association
NWR	National Wildlife Refuge
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
XRD	X-ray diffraction

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Abstract

Benton Lake National Wildlife Refuge is important for its waterfowl production and migratory bird habitat. The refuge may be threatened by the long-term accumulation of dissolved solids and selenium, either of which in high concentrations can be toxic to aquatic organisms and waterfowl. The hydrology and water chemistry of the Benton Lake basin were studied during 1991-96 to understand the processes that control the movement of dissolved solids and selenium in the basin and the fate of dissolved solids in Benton Lake. Benton Lake is a closed basin that has no outlet to allow flushing of constituents from the lake.

The basin is underlain primarily by the Cretaceous Colorado Group and Pleistocene glacial and alluvial deposits. Shallow ground water in the basin was of poor quality, containing high concentrations of major ions and nitrate. Selenium concentrations generally were elevated and ranged from less than 1 to 300 micrograms per liter (μg/L). Ground water typically was acidic because of oxidation of pyrite contained in shale and the lack of geologic materials to provide carbonate or other buffering.

Saline seeps discharging poor-quality shallow ground water are numerous in the basin. Dissolved solids and selenium discharged from seeps are precipitated during evaporation, stored in surface salts, and eventually transported to basin streams and Benton Lake by natural runoff. Reclamation using alfalfa to decrease deep percolation of precipitation was studied at one seep. Water-level declines since 1991 of as much as 4 feet in wells in and downgradient from the alfalfa field indicate that reclamation may be reducing discharge of saline and seleniferous ground water at the seep.

Tributaries to Lake Creek and Benton Lake primarily are ephemeral. Water in basin tributaries was saline, with specific-conductance values ranging from 2,190 to 15,000 microsiemens per centimeter at 25 degrees Celsius (μS/cm). Selenium concentrations ranged from less than 1 to 3,000 μg/L and varied proportionately with nitrate concentrations, indicating that selenium mobilization in the basin might be associated with agriculture.

Flow in Lake Creek, the major tributary to Benton Lake, consisted of natural runoff and irrigation drainage pumped from Muddy Creek. During 1991-92 and 1994-95, when precipitation was below or near normal, most (81-98 percent) of the streamflow in Lake Creek was pumped from Muddy Creek. In 1993, natural runoff in Lake Creek was higher, owing to above normal precipitation, and the amount of pumped water was reduced.

Water quality in Lake Creek was variable, depending on the source of streamflow. Snowmelt runoff had specific-conductance values as low as 322 μS/cm. Rainfall runoff had higher specific-conductance values, with minimum values typically between 2,500 and 5,000 μS/cm during peak flow. During low-flow conditions, specific-conductance values ranged from 2,740 to 14,000 μS/cm. Specific-conductance values of pumped water ranged from about 600 to 2,000 μS/cm. Natural runoff generally was acidic and selenium concentrations ranged from 2 μg/L during snowmelt runoff to 220 μg/L during base-flow conditions. Selenium concentrations in pumped water ranged from less than 1 to 10 μg/L.

Constituent loads to Benton Lake were determined from values of daily mean streamflow and specific conductance measured at the Lake Creek gage and relations between specific conductance and constituent concentrations in water samples. The total annual dissolved-solids load to Benton Lake during 1991-95 ranged from 5,440 to 15,109 tons. Although pumped water provided most of the dissolved solids in 4 of the 5 years during 1991-95, natural runoff is the major long-term source of dissolved solids.

The mean annual selenium load delivered to Benton Lake in 1991-95 was 132 pounds. Natural runoff, which represented only 25 percent of the total water volume entering Benton Lake, delivered 52 percent of the mean annual selenium load. Long-term data indicate that selenium loading in natural runoff may be

greater than that measured during 1991-95. All tributaries supply dissolved solids to Lake Creek but only a few supply selenium. Two perennial tributaries that receive subsurface agricultural drainage from crop-fallow farm land appear to be significant sources of selenium in the Benton Lake basin.

Annual volumes of natural runoff to Benton Lake were highly variable, ranging from 0 to 19,200 acre-feet in 1970-94. Mean annual natural runoff was 3,349 acre-feet. Annual volumes of pumped water ranged from 0 to 9,079 acre-feet during 1970-94 with a mean of 4,339 acre-feet. Although precipitation was near the long-term mean during 1991-95, the mean annual volume of natural runoff to Benton Lake was only 49 percent of the long-term mean, whereas the volume of pumped water was about 114 percent of the 1970-94 value.

Specific-conductance values in Pools 1 and 2 are lower and less variable than in Pools 3-6 because of their flow-through operation and the effect of inflows from Lake Creek. In contrast, evapoconcentration causes more variable specific-conductance values in Pools 3-6, which are the terminal basins in Benton Lake and are flooded only seasonally. The water type in Benton Lake generally is magnesium-sodium sulfate. When large amounts of pumped water have been added, bicarbonate becomes a dominant ion with sulfate.

In 1974-95, specific-conductance values in Benton Lake varied substantially from year to year and over multiyear periods. However, no significant trend of increasing specific conductance is apparent in the long-term record; therefore, accumulation of dissolved solids in Benton Lake appears to be negligible. Inventories of soluble salts in lakebed sediment indicate that dissolved solids are removed from Pools 3-6 when lakebeds are dry presumably by wind erosion. Also, some of the evaporative carbonate minerals that form are sequestered in the sediment because solubility constraints allow only partial redissolution.

Selenium concentrations in Benton Lake generally were less than 1 μg/L. As selenium is added to Benton Lake, it is removed from solution and sequestered in bottom sediment and biota by biogeochemical processes.

On the basis of the conclusion that dissolved solids do not appear to be accumulating in Benton Lake, major changes in management of Benton Lake National Wildlife Refuge may not be warranted to control salinity. The current management of seasonal flooding and drying of Pools 3-6 is a strategy that appears to be effective in managing salts. If these pools were flooded continuously and no outlet were constructed to allow flushing, dissolved-solids concentrations would be expected to increase as water added each year evaporated. If land-use changes occurred in the Benton Lake basin such that loading of dissolved solids and selenium decreased, then the potential for accumulation would be lessened. Land-use changes that would be effective include reducing the size of saline seeps and conversion of cropland to continuous vegetative cover.

INTRODUCTION

Benton Lake National Wildlife Refuge (NWR) is an important area for waterfowl production and migratory stop-over in west-central Montana. The biota utilizing the refuge could be threatened by the long-term accumulation of water-borne contaminants. Runoff entering Benton Lake contains dissolved solids and selenium, either of which in high concentrations can be toxic to aquatic organisms and waterfowl. Because Benton Lake has no outlet, managers have expressed concern that concentrations of certain chemical constituents could increase over time to the point that the lake might become unusable for its intended purpose. Knowledge of the loading of dissolved solids and selenium to the lake, the rate at which these contaminants are being removed from the lake ecosystem, and projections of contaminant accumulation are important for proper management of the refuge.

Dissolved solids and selenium are the contaminants of primary concern in Benton Lake (Palawski and others, 1991a,b; Nimick and others, 1996). In some years, specific conductance (a measure of dissolved solids) of water in Benton Lake is near or greater than 4,000 μS/cm, above which duckling growth can be adversely affected (Mitcham and Wobeser, 1988). Specific-conductance values greater than 5,000 μS/cm can result in changes in the aquatic-plant community, and thus affect marsh productivity (Donald G. Hultman, manager, Benton Lake National Wildlife Refuge, written commun., 1991). Because the concentrations of dissolved solids in natural runoff in the basin are high and because no removal mechanism has been positively identified, long-term accumulation is possible (Morrison-Maierle, Inc., 1984; Donald G. Hultman, written commun., 1991).

Concentrations of selenium higher than 2-5 μg/L in water and 2-4 μg/g in sediment have the potential to adversely affect waterfowl (Lemly and Smith, 1987; Skorupa and Ohlendorf, 1991). These relatively low concentrations are of concern because selenium is easily bioconcentrated in the food chain. Selenium has been found in elevated concentrations in samples of biota and sediment from the refuge and in water entering the refuge (Knapton and others, 1988; Palawski and others, 1991a,b; Nimick and others, 1996).

Because previous studies of hydrology and contaminants at Benton Lake NWR (Knapton and others, 1988; Nimick and others, 1996) did not address the processes and possible management implications of contaminant accumulation, a multi-agency study was initiated by the U.S. Fish and Wildlife Service (USFWS) in 1991 to address these subjects. The University of Montana conducted the primary investigation of selenium (Zhang and Moore, 1996, 1997a,b,c,d, in press, a,b) and results of that work are not published in this report. The hydrogeochemical investigation conducted by the U.S. Geological Survey (USGS) focused primarily on dissolved solids with some emphasis on selenium and is the subject of this report. Funding was provided by the USFWS and the National Irrigation Water Quality Program of the U.S. Department of the Interior.

Purpose and Scope

The purpose of this report is to present the results of a hydrogeochemical study of the Benton Lake basin. Specific objectives of this report are to describe the following:

1. The hydrology and water chemistry of ground water, saline seeps, and streamflow in the Benton Lake basin;
2. The hydrology and water chemistry of Benton Lake, including the loading of dissolved solids and selenium to Benton Lake;
3. The fate of dissolved solids within Benton Lake; and
4. The implications of dissolved-solids chemistry on management of water-bird habitat at Benton Lake NWR.

The report describes the collection and analysis of physical and chemical data from the Benton Lake basin. Emphasis is placed on the inflow of dissolved solids and selenium and the fate of dissolved solids in Benton Lake NWR. Data collected in 1990-92 for an earlier study (Lambing and others,1995; Nimick and others, 1996) and data collected in 1993-96 for this study were the primary data used in this report. Data-collection activities during 1990-96 included continuous measurement of discharge and specific conductance on Lake Creek, installation and monitoring of wells near a saline seep, periodic water-quality sampling of streams and Benton Lake, and experiments designed to assess the fate of dissolved solids in Benton Lake.

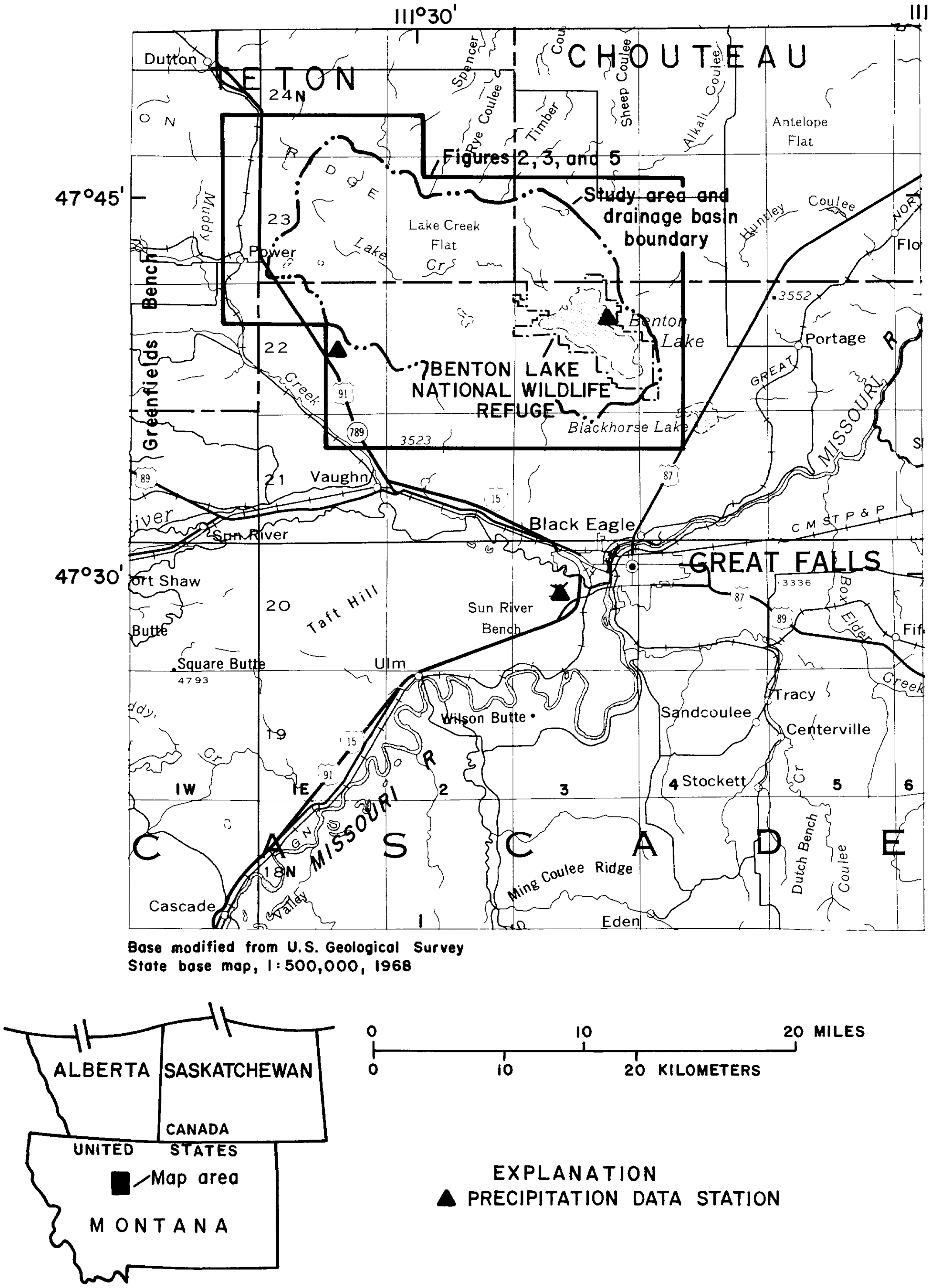
Study Area

The Benton Lake basin (figs. 1 and 2) is located north of Great Falls, Mont., in Cascade, Chouteau, and Teton Counties. The basin has no outlet and natural runoff drains to Benton Lake. The basin is about 20 mi long and encompasses about 146 mi^2. Small closed basins with a total area of 11.4 mi^2 are contained within the Benton Lake basin. The basin has little relief. Altitudes range from 3,615 to 3,850 ft above sea level in most of the basin. The hills bordering the north side of the basin rise to 4,020 ft.

Except in Benton Lake NWR, land use in the basin is almost entirely agricultural. Small grains, primarily wheat, are grown throughout the basin using crop-fallow rotations. Some former crop land that has been enrolled in the Conservation Reserve Program now supports a continuous vegetative cover. Land that is not farmed commonly is used as rangeland.

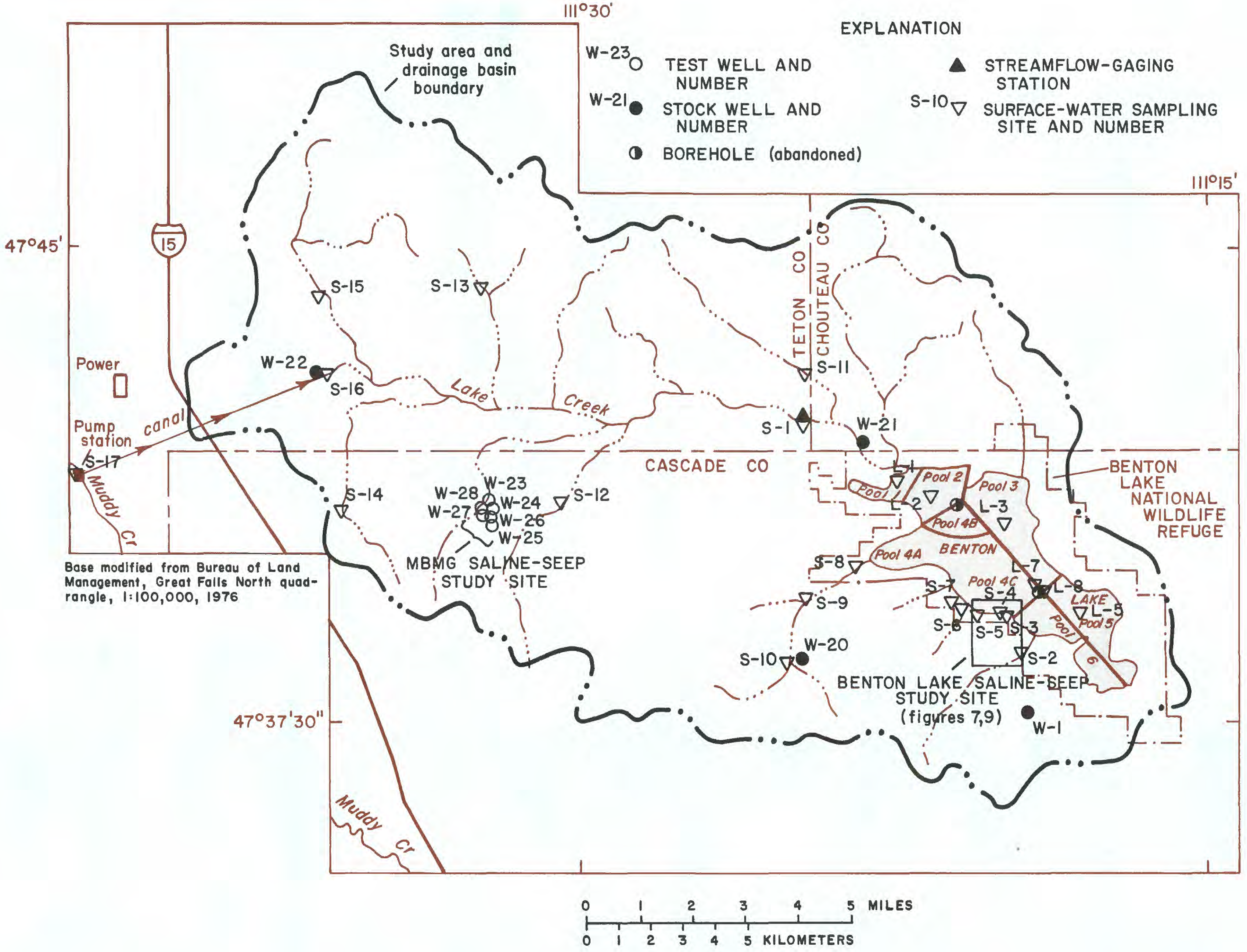
Benton Lake NWR is managed by the USFWS. The refuge consists of 12,400 acres of land—6,800 acres in uplands and 5,600 acres in wetlands. Although established in 1929, the refuge was not developed or staffed until 1961, when a pump station was constructed on Muddy Creek (fig. 2) and the marsh area was divided by dikes into six units (Pools 1-6). Most of the water entering the lake flows into Pool 1, then is conveyed to the other pools by gravity flow through canals to enhance waterfowl habitat. Pools 1 and 2 have always been managed to provide water deeper than about 3 ft all year. Depending on water availability and goals of individual refuge managers, some or all of Pools 3-6 have been flooded seasonally. When feasible, these pools are filled in the spring to enhance nesting habitat for ducks and are allowed to dry during the summer to prevent outbreaks of avian botulism. One or more of these pools are flooded again in late summer and early fall for use by migrating birds and to store water for the following spring. When flooded, water depths are shallow in Pools 3-6 and the area under water varies markedly with changes in water level.

Benton Lake NWR is important to water birds because of the substantial number of waterfowl produced annually and the migration habitat provided by its wetlands. Thirty-five species of wetland-dependent birds nest at the refuge. On a per-acre basis, Benton Lake NWR is one of the most productive duck-producing areas in North America. Annual duck production ranges from 8,000 to 40,000 ducks, primarily gadwall



Base modified from U.S. Geological Survey State base map, 1:500,000, 1968

Figure 1. Location of study area.



Base modified from Bureau of Land Management, Great Falls North quadrangle, 1:100,000, 1976

Figure 2. Location of sampling sites, the Benton Lake saline-seep study site, and the Montana Bureau of Mines and Geology (MBMG) saline-seep study site, Benton Lake basin, west-central Montana.

(*Anas strepera*), northern shoveler (*Anas clypeata*), blue-winged teal (*Anas discors*), cinnamon teal (*Anas cyanoptera*), northern pintail (*Anas acuta*), and mallard (*Anas platyrhynchos*). Other wetland-dependent birds that nest in large numbers include American avocets (*Recurvirosta americana*), marbled godwits (*Limosa fedoa*), willets (*Catoptrophorus semipalmatus*), Wilson's phalaropes (*Phalaropus tricolor*), American coots (*Fulica americana*), eared grebes (*Podiceps nigricollis*), and Franklin's gulls (*Larus pipixcan*). The refuge is a significant breeding ground for several species of special concern, including the white-faced ibis (*Plegadis chihi*), black tern (*Chlidonias niger*), common tern (*Sterna hirundo*), Forster's tern (*Sterna forsteri*), Franklin's gull, black-necked stilt (*Himantopus mexicanus*), and black-crowned night heron (*Nycticorax nycticorax*). The breeding populations at the refuge of white-faced ibis and Franklin's gull are the largest in Montana. Benton Lake NWR provides spring and fall migration habitat for 53 species. As many as 100,000 ducks, 8,000 tundra swans, 2,000 Canada geese, and significant numbers of shorebirds stop at the refuge during spring and fall migration. The refuge is recognized by the Western Hemisphere Shorebird Reserve Network as a significant area for shorebirds. Bald eagle (*Haliaeetus leucocephalus*) and peregrine falcon (*Falco peregrinus*) are bird species that are protected by the Endangered Species Act and that are attracted to the refuge during spring and fall migration when wetland prey are abundant.

Precipitation data are available for three sites in or near the Benton Lake basin (fig. 1; table 1). The Great Falls site is about 8 mi south of the basin. The Power site is 6 mi southeast of Power near the western boundary of the basin. The Benton Lake site is at the refuge headquarters near the north shore of the lake. Characterization of precipitation during the study period is based on long-term data, which are available only for Great Falls and Power (National Oceanic and Atmospheric Administration, issued annually). On the basis of the Great Falls precipitation data, 4 years (1990-92 and 1995) were near normal whereas 1993 was wet and 1994 was dry. On the basis of the precipitation data for Power, 3 years (1991-92 and 1995) were near normal, 1993 was wet, and 2 years (1990 and 1994) were dry.

Geologic Setting

The geology of the Benton Lake basin (fig. 3) is characterized by gently dipping seleniferous marine shale of the Cretaceous Colorado Group overlain locally by unconsolidated glacial and alluvial deposits. Detailed geologic mapping has been completed in much of the basin (Maughan, 1961; Lemke, 1977). Alden (1932) and Colton and others (1961) mapped the extent of the last Pleistocene continental ice sheet and glacial Lake Great Falls.

The Colorado Group is exposed from west-central Montana north to Canada and underlies the entire Benton Lake basin. Maughan (1961) and Cobban and others (1976) described the Colorado Group in detail. The unit is flat lying to gently dipping and is best exposed in the small drainages that dissect it. The Colorado Group, in ascending order, consists of the Lower and Upper Cretaceous Blackleaf Formation and the Upper Cretaceous Marias River Shale. These formations primarily are dark-gray shale with some

Table 1. Annual precipitation at three sites in or near the Benton Lake basin, Montana, 1990-95

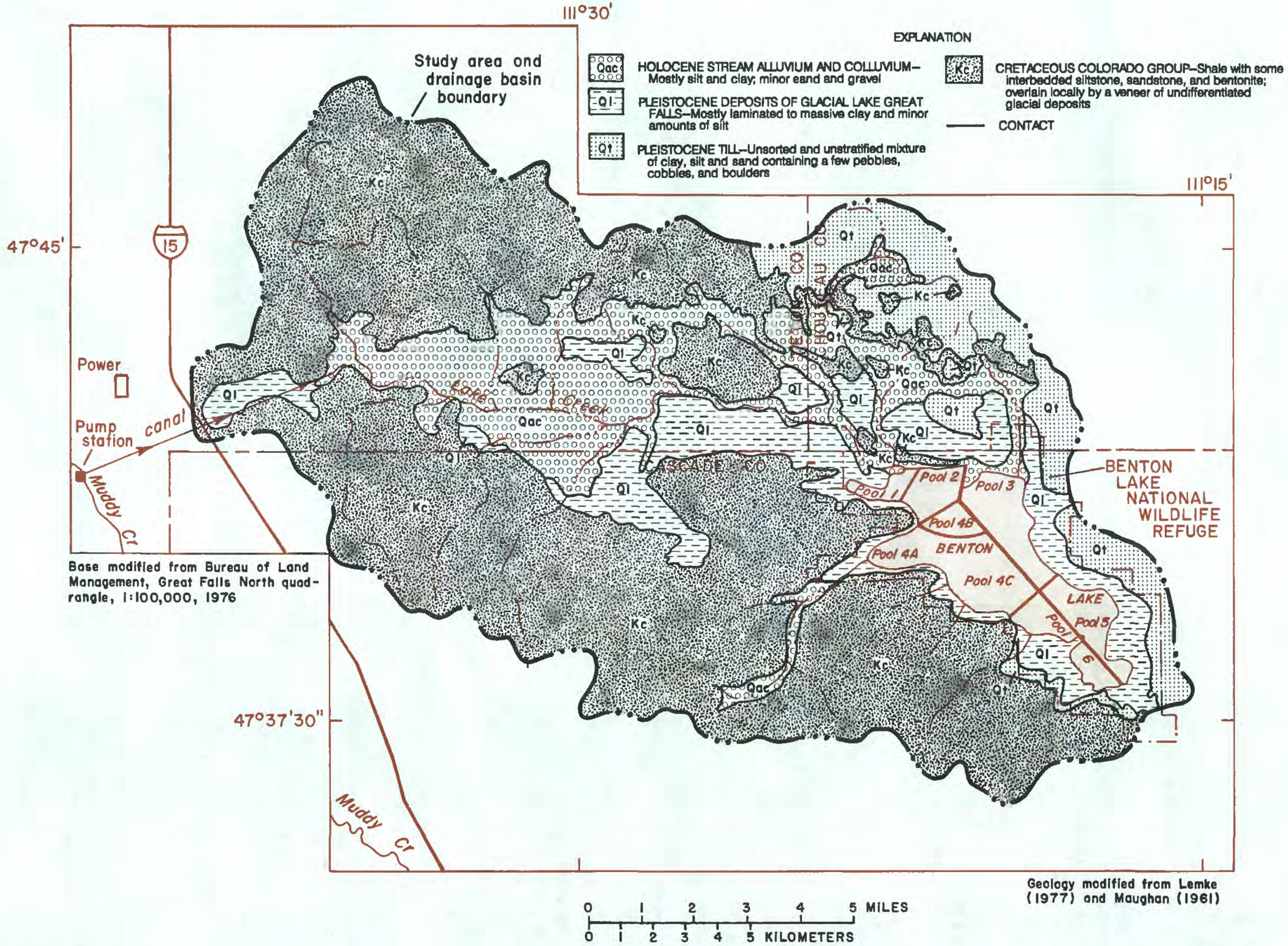
[Precipitation, in inches]

Calendar year	Great Falls[1]	Power[1]	Benton Lake[2]
1990	14.06	9.12	11.30
1991	14.04	13.00	12.93
1992	14.46	12.14	10.43
1993	23.01	21.49	17.81
1994	10.57	7.52	9.00
1995	15.50	12.97	12.90
Mean (1990-95)	15.27	12.65	12.40
Long-term mean (1961-90)	15.21	11.35	[3]13.89

[1] Data from National Oceanic and Atmospheric Administration (issued annually).

[2] Data collected by staff at Benton Lake National Wildlife Refuge (Erich Gilbert, written commun., 1994; Mindy L. Meade, written commun., 1995).

[3] Mean is for 1975-94.



Base modified from Bureau of Land Management, Great Falls North quadrangle, 1:100,000, 1976

Geology modified from Lemke (1977) and Maughan (1961)

Figure 3. Generalized geology of the Benton Lake basin, west-central Montana.

interbedded siltstone, sandstone, and bentonite. The combined thickness of both formations is about 1,500 ft.

The late Pleistocene continental ice sheet extended south to the Benton Lake basin (Colton and others, 1961). Glacial drift associated with the ice sheet was deposited north and east of Benton Lake. The deposits are primarily glacial till consisting of unsorted and unstratified clay, silt, sand, and some coarser material. Locally, glacial drift contains stratified sand and gravel alluvial deposits (Lemke, 1977). The ice sheet dammed the ancestral Missouri River and created glacial Lake Great Falls, which covered low-lying parts of the Benton Lake basin (Colton and others, 1961). Glacial-lake deposits near Benton Lake primarily are clay and silty clay and are as thick as 100 ft (Lemke, 1977).

Data Collection

Test wells were installed in August 1990 by the Montana Salinity Control Association (MSCA) at the saline-seep study site (fig. 2) adjacent to the south shore of Benton Lake. The wells were drilled with an auger or air-rotary drill rig. Casing material was 4-in. diameter polyvinyl chloride (PVC). No completion data are available for wells W-2, W-3, W-7, W-8, and W-10. In the other wells, slotted PVC screen was used for the perforated interval, which was 10-20 ft long. The annulus adjacent to the well screen was filled with silica sand. Bentonite pellets or chips were placed on top of the sand pack to form a seal 1-2 ft thick. Drill cuttings were used to fill the rest of the annulus to land surface. Water levels have been measured periodically by Benton Lake NWR staff with a steel tape since 1991 to determine any seasonal changes.

Test wells used for water-quality sampling at the Benton Lake saline-seep study site were developed using a surge block and bailer until the produced water was clear. Wells W-2, W-3, W-7, and W-8 near the seep recovered quickly during bailing. The other wells took 6-24 hours to recover so that development, as well as purging prior to sampling, was a multi-day effort. Specific conductance of ground water was measured periodically by USFWS personnel to monitor changes in dissolved-solids concentrations in ground water. Wells were bailed 3-5 times to purge casing water from the well and to ensure that the water being sampled was representative of the formation.

Ground-water samples collected for chemical analysis were obtained in stock wells with a submersible pump and in test wells with a polytetrafluoroethylene bailer. Wells were purged until at least three well volumes of water were removed and field parameters had stabilized. During purging by bailing, the water level in the well was not lowered below the top of the well screen to minimize the possibility of introducing oxygen into the formation.

A continuous-record streamflow-gaging station was established on Lake Creek in July 1990 to seasonally measure inflow to Benton Lake NWR. Daily mean values of streamflow were based on an average of recorded unit values of stage and computational methods described by Kennedy (1983) and Rantz and others (1982). Daily mean discharge values for 1990-95 were published in U.S. Geological Survey (issued annually).

A record of daily mean specific conductance was established for the period from March 1991 to September 1995 based on periodic samples and an hourly recording conductivity meter (installed March 1992). For March 1991-March 1992, specific conductance was estimated by Nimick and others (1996) as follows. During the infrequent periods of runoff, values were based on a relation between natural streamflow and specific conductance. During stable hydrologic conditions when water was pumped from Muddy Creek and during times of natural base flow, values were estimated by interpolation between periodic samples. For March 1992-September 1995, the hourly recording conductivity meter was used to construct the daily mean specific-conductance record. Daily mean specific-conductance values were published for 1992-94 in U.S. Geological Survey (issued annually).

Samples from streams and seeps were collected either by depth integration at multiple stream verticals according to methods described by Knapton (1985) or by grab sampling at culverts and sites where streamflow was very small. Instantaneous streamflow was determined at the time of sampling by direct measurement, stage-discharge rating, or estimation.

Water temperature, pH, and specific conductance were measured in the field during ground- and surface-water sampling. Field measurements and field-sample processing were performed using techniques described by the U.S. Geological Survey (1977) and Knapton (1985). Quality-control procedures used during the collection and processing of water samples were described by Knapton (1985) and Knapton and Nimick (1991). Chemical analyses of major ions, nutrients, and trace constituents were performed by the USGS National Water Quality Laboratory, Arvada, Colo. Analytical methods were described by Fishman and Friedman (1989) and Fishman (1993). Analyses of stable isotopes and tritium were performed in USGS research laboratories in Reston, Va.

Site-Identification Systems

Site numbers are used to identify ground-water and surface-water sampling sites. The site number consists of one alpha character and one or two numeric characters. The alpha character denotes sampling-site type: L, lake; S, stream or saline seep; W, ground water.

Fifteen-digit identification numbers also are used for ground-water and miscellaneous surface-water sampling sites. These numbers represent the approximate latitude and longitude of the site (first 13 digits), plus the sequence number (last 2 digits). Eight-digit station-identification numbers for routine surface-water sites represent the standard USGS numbering system for streamflow-gaging stations wherein numbers increase in a downstream direction according to geographic location within the drainage basin.

Local numbers are assigned to ground-water sampling sites according to their geographic position within the rectangular grid system used in Montana for the subdivision of public lands (fig. 4). The local number consists of 14 characters. The first three characters specify the township and its position north (N) of the Montana Base Line. The next three characters specify the range and its position east (E) of the Montana Principal Meridian. The next two characters are the section number. The next four alpha characters designate the quarter section (160-acre tract), quarter-quarter section (40-acre tract), quarter-quarter-quarter section (10-acre tract), and quarter-quarter-quarter-quarter section (2.5-acre tract), respectively, in which the well or sampling site is located. These four subdivisions of the section are designated A, B, C, and D in a counterclockwise direction, beginning in the northeastern quadrant. The last two numeric characters specify a sequence number to distinguish between multiple wells or multiple depths at a single location. For example, as shown in figure 4, well 22N02E07BBAA01 is a single well inventoried in the NE1/4(A) of the NE1/4(A) of the NW1/4(B) of the NW1/4(B) of sec. 7, T. 22 N., R. 2 E.

Acknowledgments

The author acknowledges with appreciation the many individuals who assisted in the study. Particular thanks are given to Erich Gilbert and Mindy L. Meade at Benton Lake NWR for their assistance and data-collection efforts throughout the project. Discussions with Donald G. Hultman, Stephen J. Martin, and James E. McCollum at Benton Lake NWR; Donald U. Palawski and Shannon B. Heath of the USFWS; Johnnie N. Moore and YiQiang Zhang of the University of Montana; and John H. Lambing of the USGS were invalu-

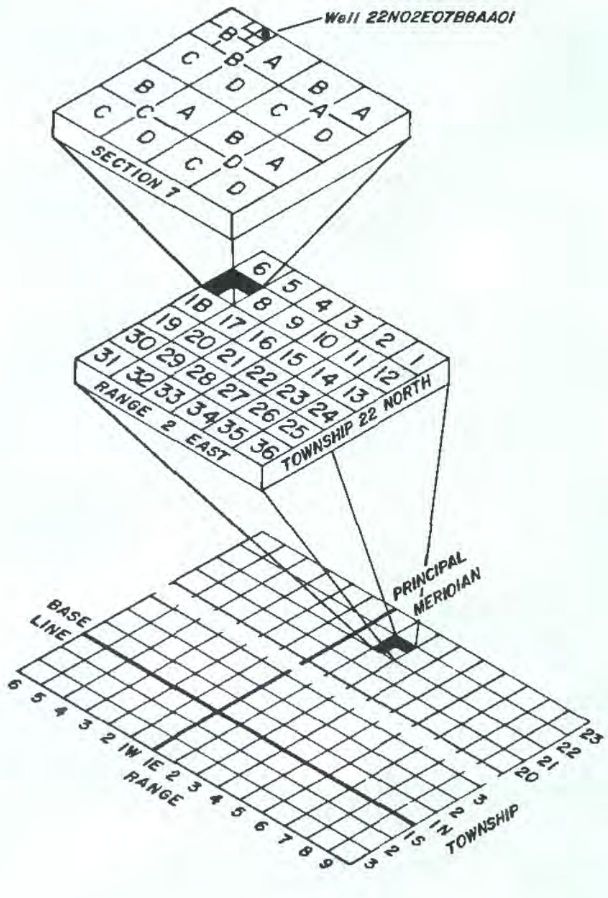


Figure 4. Numbering system for specifying geographic location of ground-water sampling sites.

able. Shannon B. Heath of the USFWS; Glenn Hockett of the MSCA; and Fred A. Bailey, David W. Briar, C. Lee Chambers, Michael S. James, Philip L. Karper, J. Roger Knapton, John H. Lambing, Timothy J. Morgan, and Joanna N. Thamke of the USGS also provided much-needed field assistance. John M. Neil of the U.S. Geological Survey provided X-ray-diffraction analyses of bulk mineralogy.

HYDROLOGY AND WATER CHEMISTRY OF GROUND WATER AND SALINE SEEPS

Previous studies (Knapton and others, 1988; Nimick and others, 1996) of ground water in the Benton Lake basin were reconnaissance level in nature. These studies determined the occurrence of selenium and dissolved solids in shallow ground water, determined if seepage from Benton Lake to shallow ground water is a significant mechanism for removing selenium or dissolved solids from the wetland, and determined the relation of ground-water sources of selenium and dissolved solids to surface water. The following discussion is an expansion of this earlier work.

Characterization of ground water in the Benton Lake basin is based on data from 26 wells (figs. 2 and 7; table 15 at back of report). Four of these were stock wells completed at depths of 27-177 ft in the Colorado Group. The rest were test wells completed at depths of 12-80 ft in the Colorado Group or overlying glacial deposits at two saline-seep study sites. At the saline-seep study site in the southwest part of the basin, six test wells were installed by the Montana Bureau of Mines and Geology (MBMG) in the mid-1970s as part of a regional study of saline seeps. The other 16 test wells were installed in 1990 by the MSCA upgradient from a saline seep that discharges along the south shore of Benton Lake.

Ground-Water Flow

Colorado Group shale is the primary water-bearing unit under much of the Benton Lake basin. Ground-water development, primarily for stock water, has been limited in the shale because of reported poor water quality and low yields. Drinking water is supplied to most residents of the basin by the Tri-County Water-Supply System, a pipeline system that imports water from the west. Prior to completion of the system, residents typically hauled water from Great Falls. Because of the sparsity of wells in the basin, sufficient water-level data were not obtained to construct a basin-wide potentiometric-surface map. Some deep wells have been drilled through the Colorado Group to underlying strata, primarily for petroleum exploration. Wells completed below the Colorado Group were reported to produce poor quality water.

Glacial-lake deposits and glacial drift overlie shale in parts of the basin. Field reconnaissance during this study showed isolated patches of glacial till or outwash in the basin that were not mapped by Lemke (1977). Although no domestic wells completed in glacial deposits were sampled, water in glacial deposits could be the source of water for some saline seeps in the basin.

Because of the topographic position of the Benton Lake basin above land to the east, ground water might flow east from the basin and discharge to wetlands between Benton Lake and the Missouri River. If Benton Lake is hydraulically connected to ground water flowing eastward, chemical constituents in Benton Lake could be transported to wetlands to the east. Any water that percolates downward from Benton Lake probably carries little, if any, selenium because selenium is not mobile under the reducing conditions presumed to exist in the sediments below the lake. However, many other dissolved constituents would be transported. In 1991, two boreholes were drilled in Benton Lake at the junction of the dikes separating Pools 3, 4C, 5, and 6 and at the west end of the dike separating Pools 2, 3, and 4B (fig. 2) to determine the lithology and thickness of underlying materials. Both holes were drilled to a depth of 80 ft through gray, silty, clayey lakebed sediments. The borehole results support Lemke's (1977) observation that the thickness of glacial-lake sediments exceeds 100 ft near Benton Lake. On the basis of the assumed low permeability of the lakebed sediments, Nimick and others (1996) concluded that little water is lost from Benton Lake to ground water.

Ground-Water Quality

Ground-water quality of samples collected in the Benton Lake basin was poor. However, the data presented in table 16 (at back of report) may not be entirely representative of ground water in the basin, because most of the samples were collected from closely spaced wells at the two saline-seep study sites. Ground-water samples can be divided into two general groups according to depth of the water-bearing zone.

Water-quality characteristics of deep (>100 ft) ground water were determined from samples from wells W-20 and W-22 completed in shale. Although well W-1 is deep (177 ft), the depth of the water-bearing zone is unknown and chemical data from this well were not used in this analysis. Considering the similarity of water-quality characteristics of the sample from

W-1 and shallow ground water, the water-bearing zone of W-1 may be shallower than the well depth. Deep ground water had sodium as virtually the only cation whereas sulfate and bicarbonate were the predominant anions. Chloride concentrations were relatively low (14 and 39 mg/L), dissolved-solids concentrations were moderate (2,350 and 4,210 mg/L) (for the area), and pH was basic (7.7 and 9.1). Based on nitrate concentrations (<0.1 and 0.50 mg/L), redox conditions probably were reducing. Consequently, even though the shale is seleniferous, dissolved selenium concentrations were very low (<1 and 1 µg/L).

The proportion and amount of constituents in samples of shallow (<100 ft) ground water were different from those of water from deep shale. Increased concentrations of calcium, sulfate, chloride, and magnesium contributed to much higher dissolved-solids concentrations in the shallow ground water than in deeper ground water. Because of the lack of carbonate or other buffering minerals in the shale, acid produced from oxidation of sulfides in the marine shale (Mermut and Arshad, 1987) is not completely neutralized and pH values (3.7-7.2) in shallow ground water, for the most part, were acidic. Nitrate concentrations were high (1.7-55 mg/L), probably either because cultivation caused increased oxidation of the organic nitrogen that had accumulated in the soil prior to farming (Kreitler and Jones, 1975) or because dryland crop-fallow farming causes deep leaching of nitrate (Custer, 1975). On the basis of nitrate and dissolved-oxygen concentrations, redox conditions were oxidizing and, consequently, selenium concentrations generally were high. Selenium concentrations ranged from 0.8 to 300 µg/L. The selenium in ground water presumably originated from weathering of rocks of the Colorado Group, which had a selenium concentration range of 0.1 to 1.1 µg/g in drill cuttings from sites W-2, W-11, W-14, and W-17 (sites W-53 to W-56 in Lambing and others, 1994, table 13).

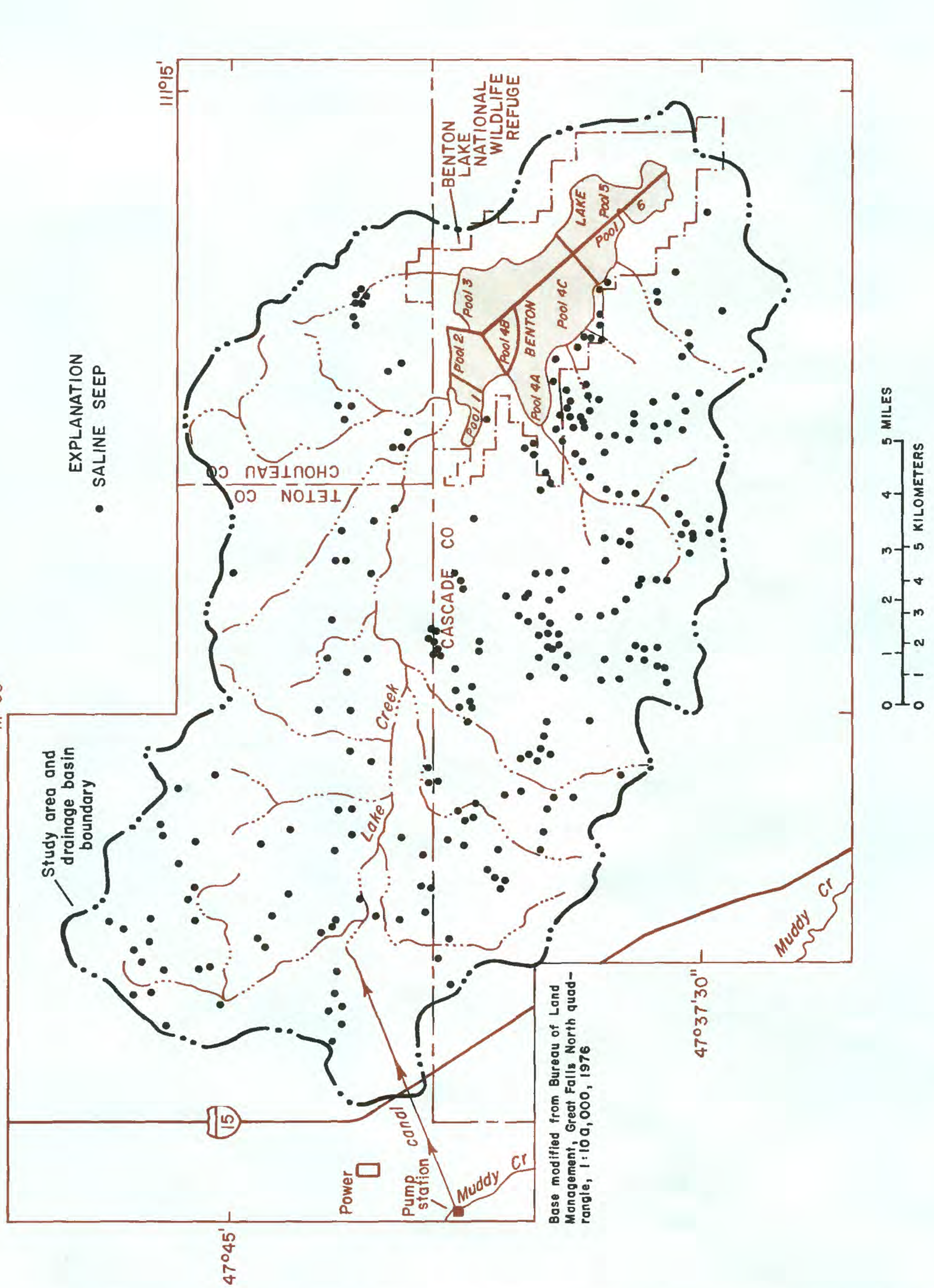
Trace-metal concentrations in acidic samples of shallow ground water were high. Dissolved concentrations in the samples from four test wells at the Benton Lake saline-seep study site were as high as 100 µg/L cadmium, 21,000 µg/L manganese, and 4,900 µg/L zinc in samples with pH values less than about 6 (sites W-53 to W-56 in Lambing and others, 1994, table 11). At the MBMG study site, the samples with pH values of 3.7-4.2 had concentrations as high as 79,000 µg/L aluminum, 60 µg/L cadmium, 1,400 µg/L lead, 14,000 µg/L manganese, 5,900 µg/L nickel, and 8,200 µg/L zinc (Montana Bureau of Mines and Geology, unpub. data).

Water quality in shallow shale of the Benton Lake basin was similar to ground-water quality in other parts of north-central Montana underlain by the Colorado Group (Donovan and others, 1981). Samples from 53 wells sampled by Donovan and others (1981) and completed in shale or overlying glacial deposits typically had a sodium-magnesium sulfate composition and mean concentrations of dissolved solids and selenium of 9,260 mg/L and 308 µg/L, respectively. The major difference between samples from north-central Montana and those from the Benton Lake basin was the range of pH values. Most north-central Montana samples had pH values greater than 7, and these probably came from wells completed in glacial deposits, which have sufficient carbonate material to neutralize acid produced by sulfide oxidation. The acidic samples reported by Donovan and others (1981) probably came from areas in unglaciated parts of north-central Montana similar to the Benton Lake basin, where wells are completed in shale.

Saline Seeps

Saline seeps are common in the Benton Lake basin and in the northern Great Plains of Montana (Miller and Bergantino, 1983). The alternate crop-fallow rotation widely used in this semiarid region causes increased areal recharge to shallow ground water by partial elimination of vegetation and the associated water consumption in the root zone. Salts that had accumulated in the vadose zone under pre-farming conditions are dissolved by the increased infiltration of precipitation and transported to shallow ground water. Ground water flows toward nearby hill slopes or low-lying areas where it discharges and evaporates, forming areas of salt precipitates and highly saline water (Halvorson and Black, 1974; Doering and Sandoval, 1976; Miller and others, 1981). Seeps can be reclaimed by decreasing the amount of precipitation infiltrating through the root zone (Miller and others, 1981). Recharge can be reduced by growing deep-rooted plants such as alfalfa on the recharge area of the seep or by changing from crop-fallow rotation to continuous cropping. Recharge areas can be defined by measuring water levels in shallow test wells installed upgradient from the seep.

Saline seeps in the Benton Lake basin (fig. 5) were mapped in 1993 by Erich Gilbert (Benton Lake National Wildlife Refuge, written commun., 1993) using aerial photographs and field reconnaissance. More than 240 seeps were mapped in the basin. Most of the seeps are located in the south and west parts of the basin in areas underlain by rocks of the Colorado Group (fig. 3). Seeps were identified as areas where surface salts accumulate, the native upland vegetation has been replaced with salt-tolerant plants, and the



Base modified from Bureau of Land Management, Great Falls North quadrangle, 1:100,000, 1976

Figure 5. Saline seeps in the Benton Lake basin, west-central Montana (Erich Gilbert, Benton Lake National Wildlife Refuge, written commun., 1993).

ground generally is saturated with water. The extent of seeps prior to the introduction of crop-fallow farming is not known but, on the basis of evidence from other parts of Montana (Miller and others, 1980), the size and number of saline seeps in the Benton Lake basin probably has increased during the past 50 years.

Most seeps do not have measurable discharge. Some have measurable discharge for a short period after snowmelt or intense precipitation has recharged the local ground-water system. The seeps along the south shore of Benton Lake are typical of the other seeps in the basin. Only some of the seeps along the south shore had measurable discharge that could be sampled. Runoff during snowmelt or precipitation can flush salts from seeps into drainages.

Water-quality data for seeps in the Benton Lake basin are available only for the seeps along the south shore of Benton Lake (sites S-3 to S-7, fig. 2; table 17 at back of report). Specific-conductance values ranged from 5,900 to 27,500 µS/cm. Values of pH and concentrations of major ions, nitrate, and selenium varied considerably. Samples from site S-3 were acidic (pH = 4.7 and 5.0) whereas samples from other sites were basic (pH = 7.1-8.5). Differences in pH probably are caused by differing lithologies in the ground-water system upgradient from each seep. Ground water flowing solely through shale probably does not come in contact with sufficient carbonate or other buffering minerals to buffer acid-forming oxidation reactions. Ground water in glacial drift or sandstone lenses within the Colorado Group shale either may have sufficient contact with carbonate for neutralization or may lack sufficient pyrite or organic sulfur to generate acid. On the basis of the presence of selenium in seep water, the latter hypothesis probably is not true because selenium and pyrite commonly are associated in shale. Selenium concentrations ranged from 2 to 500 µg/L, with higher concentrations occurring in samples with higher nitrate concentrations. This correlation may indicate that reducing conditions (evidenced by low nitrate concentrations) at the seeps or in the upgradient ground-water system immobilize selenium.

Most ground water discharged to seeps does not reach Lake Creek or Benton Lake because topographic gradients are small and evaporation rates, especially during warm periods, are high. In contrast, most of the salt and selenium load carried to the surface by ground water eventually is dissolved and transported to Benton Lake by precipitation runoff. Evaporite minerals precipitate as ground water evaporates in discharge areas. Slightly soluble salts such as calcite and gypsum precipitate first, mostly in the subsurface, as evapotranspiration concentrates discharging water (Timpson and others, 1986; Skarie and others, 1987; Miller and others, 1989, 1993). Formation of these salts in the subsurface reduces the dissolved-solids load discharged at seeps. Efflorescent crusts consisting of highly soluble sodium and magnesium sulfate minerals form on the surface of seeps and along channels (Whittig and others, 1982; Keller and others, 1986a,b).

Although formation of salts in the subsurface may reduce the dissolved-solids load discharged to seeps by ground water, selenium loads probably are not reduced. Selenium in the discharging ground water is preferentially concentrated in the efflorescent salts as opposed to the subsurface salts. Two surface-sediment samples collected by Knapton and others (1988, table 16, sites 24 and 25) at saline seeps near Benton Lake had total selenium concentrations of 1.1 and 6.7 µg/g. Presser and others (1990) found that the selenium in magnesium and sodium salts in the western San Joaquin Valley is in the form of selenate. They postulated that the selenate (SeO_4^{2-}) anion can substitute for sulfate (SO_4^{2-}) in the open lattice structure of magnesium and sodium salts and that these salts provide a temporary sink for selenium. In contrast, selenium does not substitute in calcium sulfate minerals such as gypsum. The high initial concentrations of selenium in water samples collected from Lake Creek on July 25, 1990, when pumped water flushed salts from the previously dry channel, provide evidence that the efflorescent salts that form in the basin contain selenium (fig. 6). The efflorescent salts distributed throughout the basin and in the Lake Creek channel are dissolved quickly and transported to Benton Lake by runoff from snowmelt or heavy rainstorms or by water pumped to Lake Creek from Muddy Creek.

Benton Lake Saline-Seep Study Site

The USFWS and MSCA initiated a pilot program in 1990 to study and reclaim the saline seep located at the south end of the dike between Pools 4C and 6 of Benton Lake. The seep covers about 10 acres at the base of a hillslope. The seep primarily is unvegetated and salt crusts form during dry periods as discharging ground water evaporates. Private land upgradient from the seep has been farmed using crop-fallow rotation by the current landowner since 1941 and possibly since the mid-1930s by a previous landowner (Mindy L. Meade, Benton Lake National Wildlife Refuge, written commun., 1995) Similar to other saline seeps in Montana (Halvorson and Black, 1974; Doering and Sandoval, 1976; Miller and others, 1981), the size of the seep probably has increased because of decades of crop-fallow rotation farming on land upgradient from the seep. Discharge of saline water from the seep and precipitation runoff that flushes accumulated surface salts cause

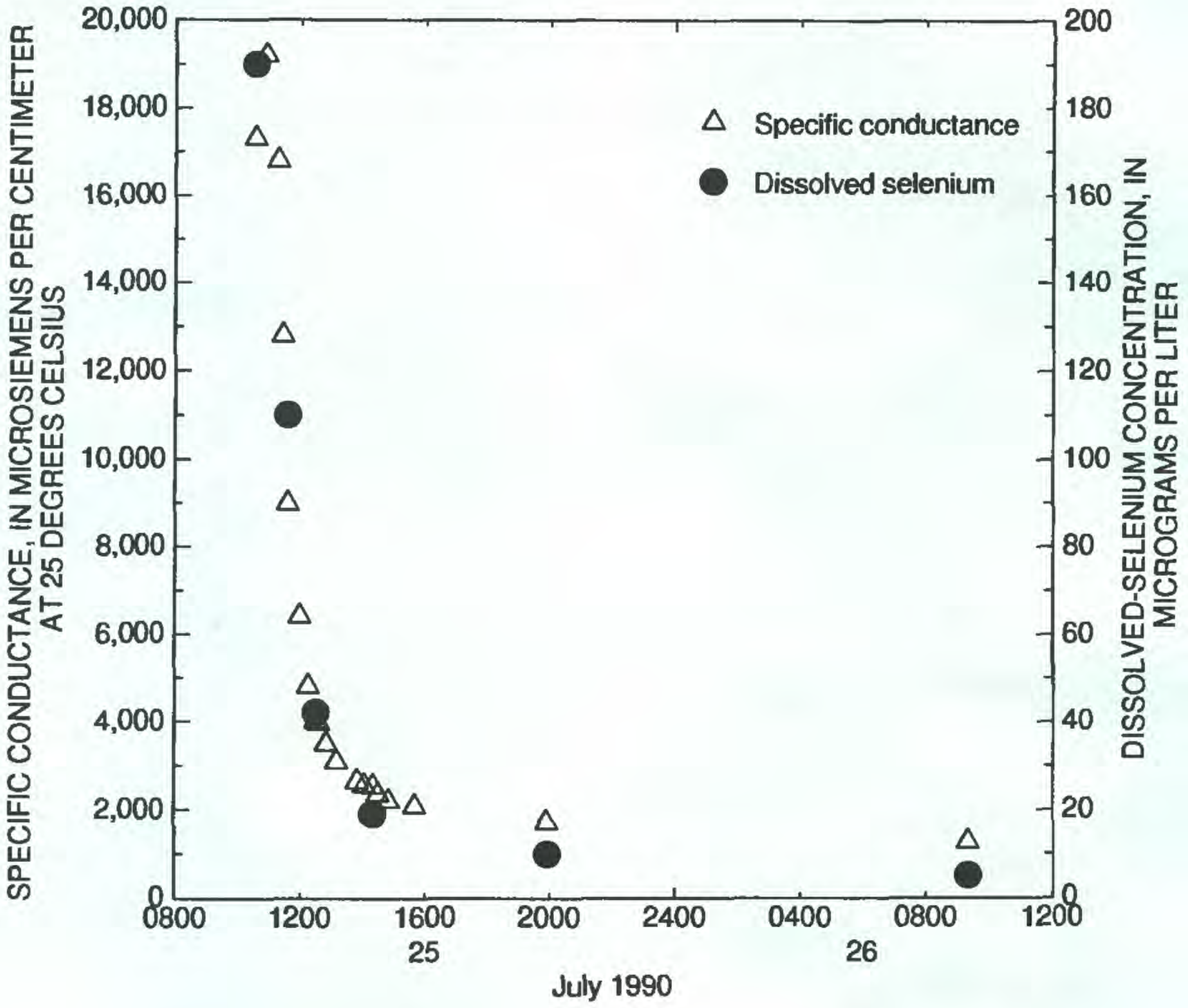


Figure 6. Specific conductance and dissolved-selenium concentration of water samples collected from Lake Creek (site S-1, fig. 2), Montana, as water pumped from Muddy Creek flushed salts from the channel. No flow occurred in Lake Creek for the 15 days prior to collection of the first sample. Streamflow was an estimated 5 cubic feet per second when the first sample was collected at 1032 hours on July 25, 1990, and increased to 16 cubic feet per second at 1955 hours the same day. Streamflow remained stable through July 26.

elevated concentrations of dissolved solids in nearby parts of Pools 4C and 6.

Sixteen test wells (table 2) were drilled upgradient from the seep by the MSCA in August 1990 to measure ground-water levels and delineate the extent of the recharge area of the seep. After delineation of the recharge area, the USFWS contracted in 1991 with the owner of the land adjacent to the refuge to modify farming practices according to recommendations made by MSCA. The hydrology of the saline seep and the effectiveness of the changed farming practices can be assessed from monitoring data collected by the USFWS and USGS since 1991.

The Benton Lake saline-seep study site is underlain by shale and glacial deposits. The Lower and Upper Cretaceous Bootlegger Member of the Blackleaf Formation underlies the entire site (Lemke, 1977). This unit primarily is shale with some sandstone lenses. As indicated by lithologic logs of the test wells upgradient from Benton Lake (wells W-4, W-11, and W-13 to W-18), glacial deposits 6-46 ft thick overlie the shale. These deposits were not mapped by Lemke (1977), but their presence is consistent with findings of Colton and others (1961), who indicated that the study site had been covered by a continental ice sheet. These glacial deposits primarily consist of silty, clayey sand that locally contains gravel. Glacial-lake deposits 4-14 ft thick that consist primarily of silty clay overlie the Bootlegger Member near the shore of Benton Lake (wells W-2, W-3, W-7, and W-8).

A potentiometric-surface map constructed from water-level data collected June 25, 1992 (table 2), at the Benton Lake saline-seep study site is shown in figure 7. The configuration of the potentiometric surface would not change significantly if water-level data collected at some other time during the study had been used because changes in water levels were small. The potentiometric surface defines ground-water flow directions near the seep and the location of the recharge area for the seep. Ground water is assumed to flow perpendicular to the potentiometric contours. The

Table 2. Test wells completed at the Benton Lake saline-seep study site, Montana

[Principal aquifer: Qt, Quaternary glacial till; Kbb, Lower and Upper Cretaceous Bootlegger Member of Blackleaf Formation. Symbol: --, no data]

Site number (fig. 7)	Local number	Principal aquifer	Altitude of land surface (feet above sea level)	Depth of well (feet below land surface)	Water level, 06-25-92 (feet below land surface)	Altitude of water level, 06-25-92 (feet above sea level)
W-2	22N03E22AACB02	Qt/Kbb	3,620	12	4.31	3,615.7
W-3	22N03E22ADAB03	Qt/Kbb	3,629	17.5	.89	3,628.1
W-4	22N03E22ADCB04	Kbb	3,671	60	36.94	3,634.1
W-7	22N03E22AACC07	Qt/Kbb	3,633	16	5.03	3,628.0
W-8	22N03E22ABDB08	Kbb	3,627	13.5	9.17	3,617.8
W-9	22N03E22DBAA09	Kbb	3,668	38	21.08	3,646.9
W-10	22N03E22BDDA10	Qt/Kbb	3,661	17	dry	--
W-11	22N03E22ADBB11	Kbb	3,661	49	30.67	3,630.3
W-12	22N03E22ABCC12	Kbb	3,639	40	19.19	3,619.8
W-13	22N03E22ACAC13	Kbb	3,668	60	33.70	3,634.3
W-14	22N03E22ACCD14	Kbb	3,678	59	33.80	3,644.2
W-15	22N03E22CAAA15	Kbb	3,687	48	30.98	3,656.0
W-16	22N03E22CDAA16	Kbb	3,705	60	50.27	3,654.7
W-17	22N03E22CACD17	Kbb	3,714	78	49.86	3,664.1
W-18	22N03E22CAAB18	Kbb	3,690	65	53.66	3,636.3
W-19	22N03E22DBCA19	Kbb	3,695	62	43.49	3,651.5

recharge area is a long, relatively narrow area, about 52 acres in size, that extends south and southwest from the seep. The recharge area may extend farther to the southwest but no wells exist to define flow paths in this area. A geologic section along a line approximately coincident with a ground-water flow path through the center of the recharge area to the seep is shown in figure 8.

The recharge area includes refuge-owned land with native upland vegetation and parts of three privately owned farm fields (fig. 9). Prior to 1991, wheat was grown in each field. The west field was farmed using an alternate crop-fallow rotation on the entire field. The north and east fields were farmed using an alternate crop-fallow rotation on strips of land within each field. In 1991, the crop-fallow rotation was abandoned in the north field and, on the basis of a recommendation from the MSCA for saline-seep remediation, alfalfa was planted to reduce infiltration and ground-water recharge. When fully established as a perennial cover, alfalfa has roots that extend deep into the vadose zone. The plant can utilize much, if not all, of the annual precipitation and essentially eliminate deep percolation of precipitation. The plant also can utilize preexisting soil moisture that may have accumulated during the time crop-fallow rotation was used on overlying land (Brown, 1972, 1977). The 1991 planting of alfalfa generally was not successful because of drought conditions; the field was replanted in 1992. In 1993, the alfalfa stand developed substantially. No changes in farming practices were made in the east and west fields during the study period.

Water levels were measured periodically in the test wells from February 1991 through December 1995 (fig. 10). Upgradient from the alfalfa field, the water table is about 50 ft deep and water levels in general did not change significantly during 1991-95. Water levels increased about 4 ft during 1991-95 in W-16 and declined about 1 ft in W-17. Water levels in wells W-15 and W-18 (data not shown) fluctuated less than 2 ft during 1991-95 and exhibited no consistent trend. Annual precipitation patterns and the crop-fallow rotation used in this area may affect water levels.

Water levels in wells in the alfalfa field and near the seep generally declined during 1991-95. In (or near) the alfalfa field, water levels declined about 4 ft in well W-11, 2-3 ft in wells W-13 and W-14, and about 2 ft in well W-4 (data not shown). Water-level declines were greater during 1991-93 than during 1994-95. Near the seep, water levels declined about 3 ft in well W-3, about 4 ft in well W-7, and a little more than 1 ft in well W-8 (data not shown) during 1991-95. Water level had no net change in well W-2, which is the well nearest Benton Lake and the seep; however, water levels fluctuated about 1.5 ft in well W-2. The surrounding water table may need to decline farther before

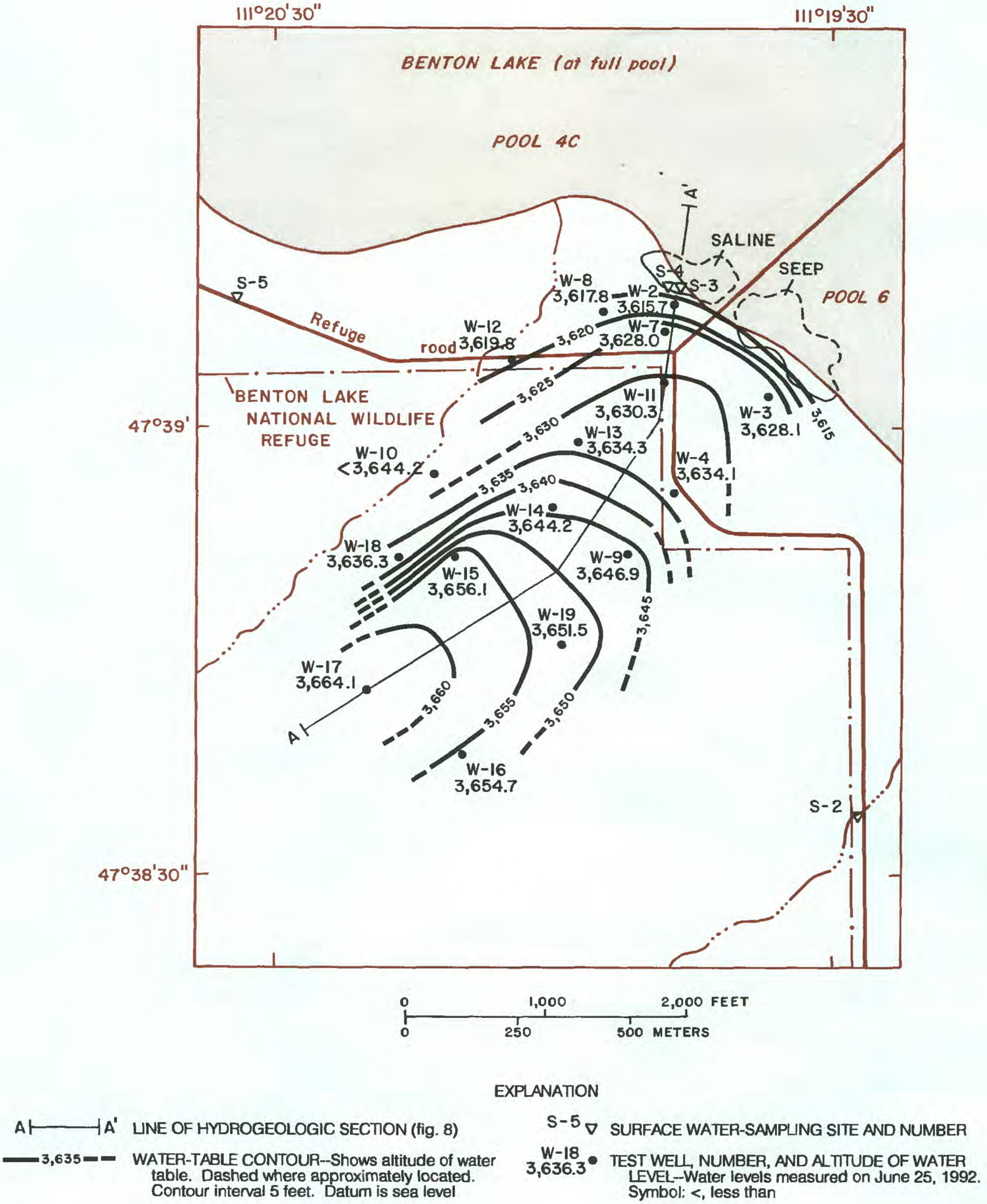


Figure 7. Altitude and configuration of the water table in June 1992 at the Benton Lake saline-seep study site, west-central Montana.

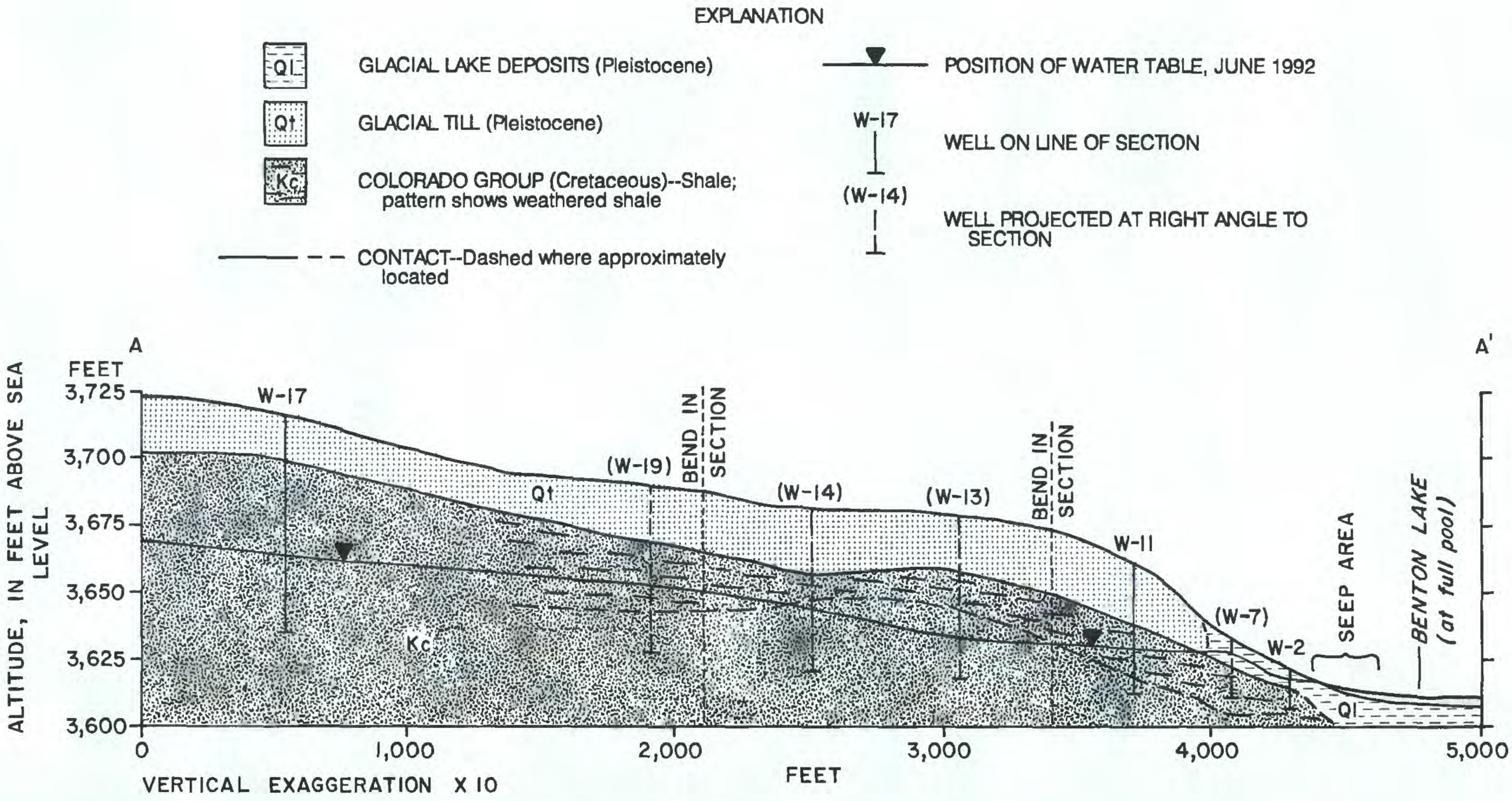


Figure 8. Hydrogeologic section of the Benton Lake saline-seep study site, west-central Montana. Line of section is shown in figure 7.

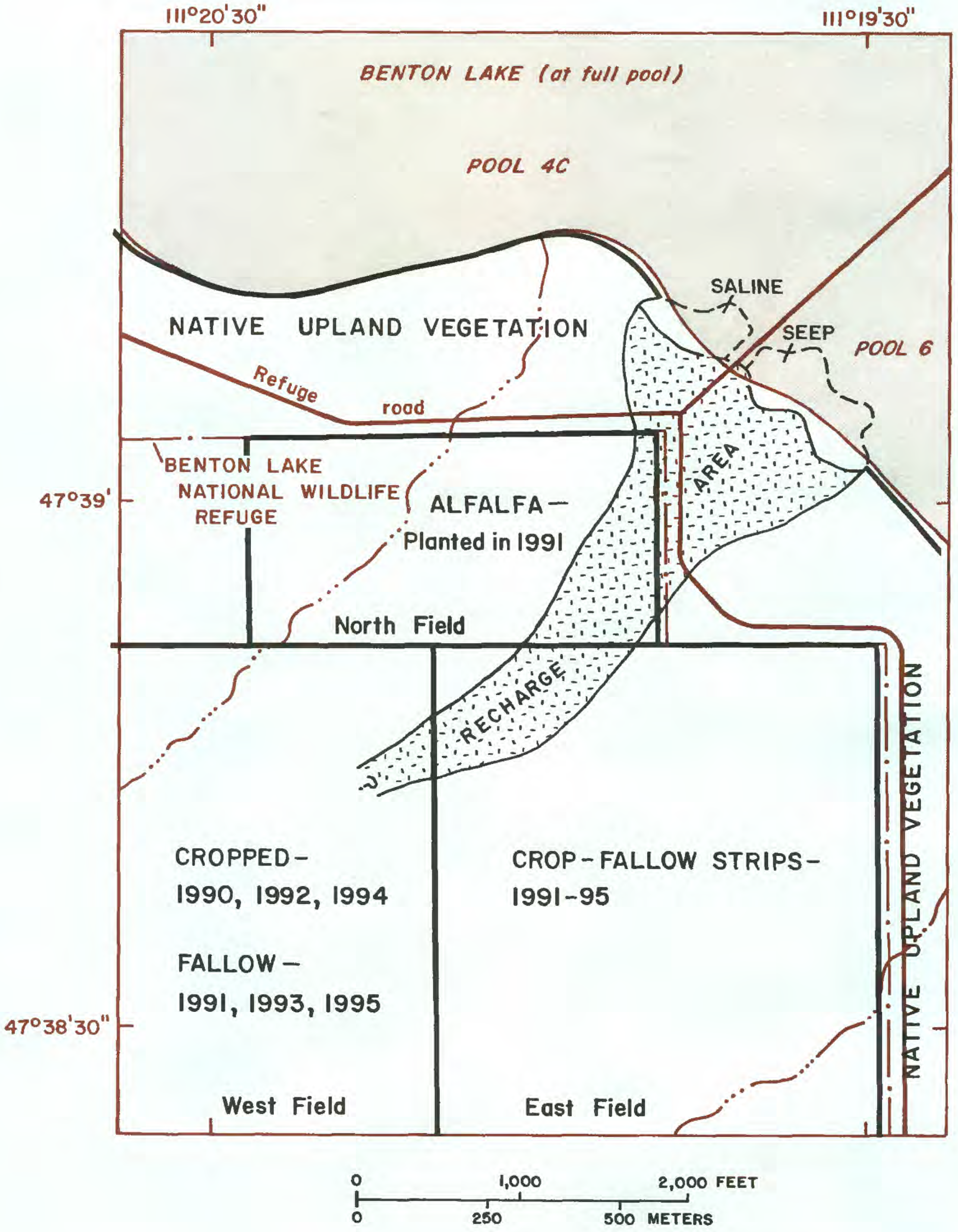


Figure 9. Vegetation and land use at the Benton Lake saline-seep study site, west-central Montana.

water-levels decline in well W-2. Water-level declines were greatest during the summer, possibly in response to evapotranspiration from the shallow water table.

The water-level declines during 1991-95 beneath and downgradient from the north field could be due to the establishment of alfalfa and consequent reduced recharge from the field. However, although the data are suggestive, a precise cause-and-effect relation cannot be established for several reasons. Part of the decline in 1991-92 may be due to below-normal precipitation

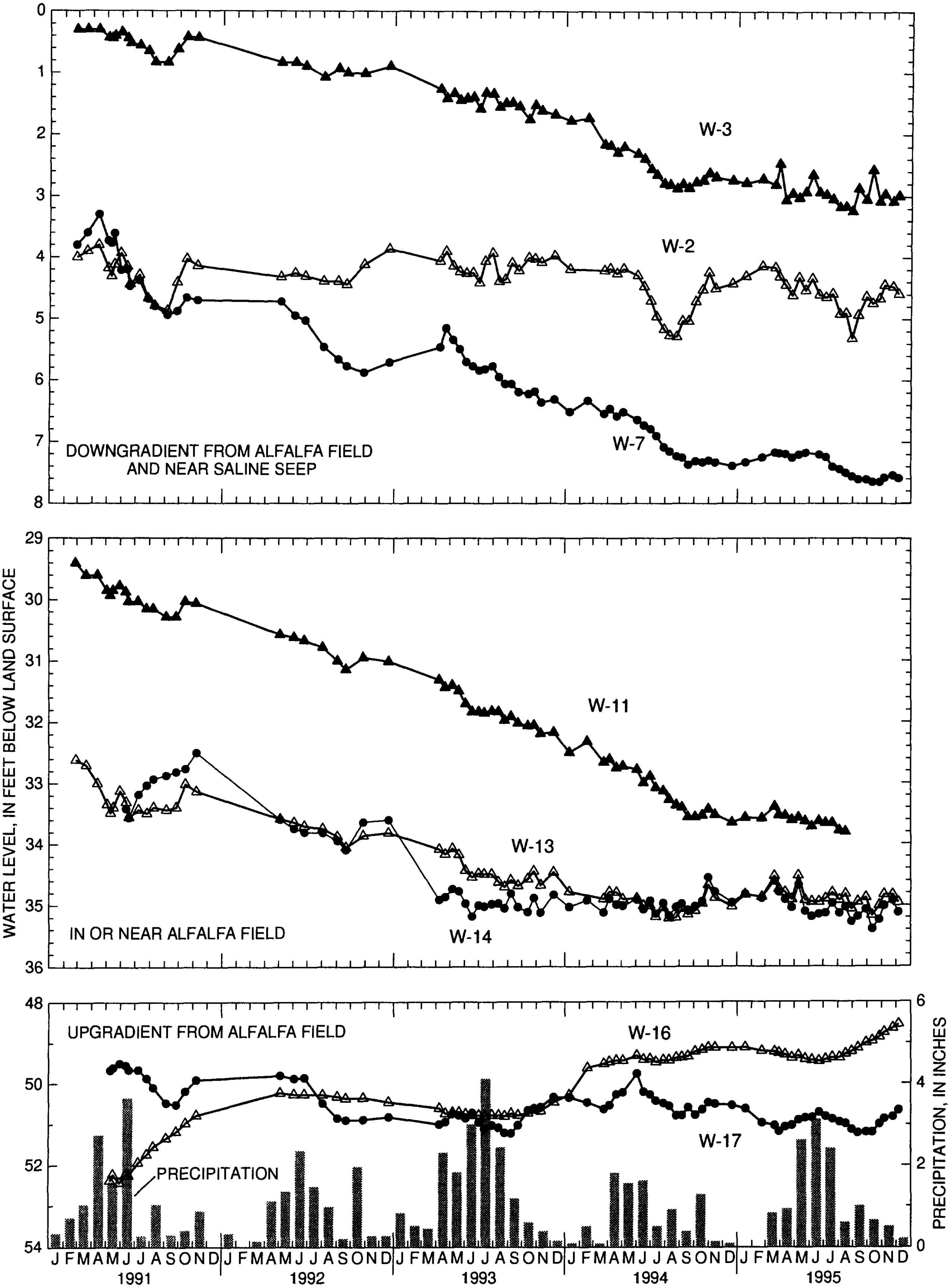


Figure 10. Hydrographs of test wells at the Benton Lake saline-seep study site and precipitation data at Benton Lake National Wildlife Refuge, Montana, 1991-95. Water-level and precipitation data from staff at Benton Lake National Wildlife Refuge (Erich Gilbert, written commun., 1994; Mindy L. Meade, written commun., 1995).

in 1990 and not to alfalfa-induced reduction in recharge because the alfalfa was not well established, particularly in 1991. No water-level data are available to establish water-level trends prior to 1991. Also, the smaller decline observed in wells W-13 and W-14 during 1994-95 is problematic, especially because precipitation in 1994 was low. The reason for this change in the 1991-95 water-level trend is not clear but may be due to a delayed effect of recharge in 1993, a relatively wet year.

The decrease in water levels in the recharge area of the seep between 1991 and 1995 indicates that the water-table gradient has been lessened and discharge at the seep has been reduced. However, the decrease in discharge was not quantified for the reason that discharge from the seep is difficult to measure. Discharge was not measured for the entire seep because discharge does not occur in discrete channels but rather as diffuse discharge over a large area and through evapotranspiration. Ground-water flow to the seep could have been estimated if the transmissivity of the aquifer were known. Monitoring of the surface area of the seep, which was not done during the study, potentially could indicate whether the seep is enlarging or contracting, although this process may occur slowly as the edge of vegetation gradually advances or retreats in response to soil saturation and salinity.

Water-quality data for the saline-seep study site are available from four test wells (table 16) and two surface-discharge sites at the seep (table 17). Test wells W-2, W-11, W-14, and W-17 are located south and southwest of the seep along a 4,000-ft long line approximately coincident with a ground-water flow path through the center of the recharge area of the seep (fig. 7). Seep samples were collected at sites S-3 and S-4 on the Pool 4C side of the seep.

As indicated by the one set of water samples collected in June 1991, the chemistry of ground water appears to evolve along the flow path defined by the four test wells. Water at upgradient wells W-17 and W-14 had specific conductance values of 9,800 and 10,100 µS/cm and a near neutral pH (7.2); sodium and sulfate were the dominant ions. Downgradient in samples from wells W-11 and W-2, specific-conductance values (14,000 and 14,700 µS/cm) were higher and pH (5.0 and 6.7) was acidic; magnesium and sulfate were the dominant ions. The selenium concentration (19 µg/L) in the sample from well W-17 was relatively low. Selenium concentrations increased from 200 to 300 µg/L in the downgradient direction in samples from wells W-14, W-11, and W-2.

On the basis of ground-water ages determined from tritium data, part of the observed chemical evolution probably is due to mixing because water appears to enter this flow system from two directions. At well W-17, the water sample had a tritium concentration of <0.3 TU, indicating that ground water was recharged prior to 1940 (Robertson and Cherry, 1989) at this site. Water at well W-17 is assumed to flow to the northeast and north toward the other wells. Water samples from the other three wells had tritium concentrations of 2.5-13 TU, indicating that recharge occurred after 1952 or, more likely, that the sampled water was a mixture of pre-1940 water flowing from the southwest and post-1952 water recharged from above. These tritium data indicate that recharge probably has occurred from the farmland overlying wells W-2, W-11, and W-14 and that the crop-fallow farming used in the recharge area (fig. 9) could have affected ground water in the area.

Other water-quality data also indicate that ground water is being recharged from overlying crop-fallow farmland. High nitrate concentrations (13 and 20 mg/L) in wells W-14 and W-11 are consistent with other saline-seep studies that have demonstrated a relation between crop-fallow farming and elevated nitrate concentrations in ground water (Custer, 1975; Kreitler and Jones, 1975). Oxygen and hydrogen stable-isotope ratios in samples from wells W-2, W-11, W-14, and W-17 plot close to the meteoric water line for southern Saskatchewan (Fritz and others, 1987) (fig. 11). These isotopic data indicate little evaporation has occurred and that the high concentrations of dissolved constituents in samples from these wells were derived from mineral dissolution along the flow path rather than evaporative concentration of more dilute water. Schwartz and others (1987) reached the same conclusion with similar isotopic data for shallow ground-water samples collected near saline seeps in southern Alberta.

Water collected at the seep in 1986 and 1994 was more saline than ground water at well W-2, probably due to evapoconcentration caused by evapotranspiration of the shallow ground water near the seep. Specific-conductance values (21,000-27,500 µS/cm) of samples from sites S-3 and S-4 were high, making this water undesirable for water birds in Benton Lake. Although the specific conductance of samples from the two sampling sites in the seep were similar, the trace-element chemistry at these two sites was different. Samples from site S-3 were acidic (pH = 4.7 and 5.0) and contained high concentrations of nitrate (46 mg/L) and selenium (320 and 500 µg/L). Like specific-conductance values, these concentrations are somewhat higher than in samples from well W-2. The sample from site S-4 was basic (pH = 8.3) and did not contain high concentrations of nitrate (0.13 mg/L) and selenium (10 µg/L). This water appears to originate from

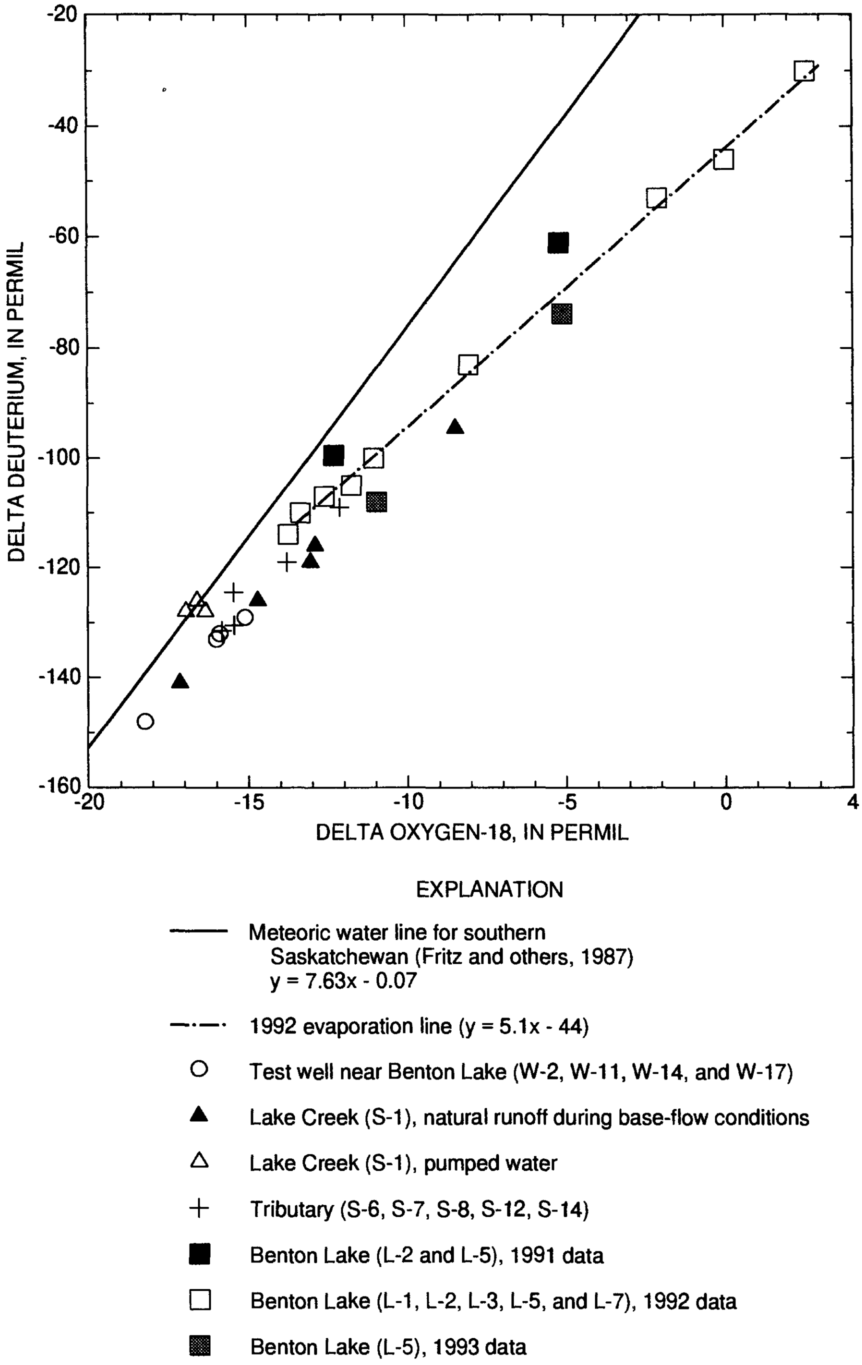


Figure 11. Relation of delta oxygen-18 and delta deuterium values in samples of ground and surface water from the Benton Lake basin, Montana.

a ground-water source with reducing conditions that limit nitrate and selenium concentrations and prevent acid-forming pyrite oxidation. The relation between this ground-water source and the ground-water system described by the four test wells and site S-3 is not known.

The primary effect of discharge of saline water from the seep to Benton Lake is water-quality degradation and selenium accumulation in sediment in the borrow ditches that parallel the dike between Pools 4C and 6. Specific-conductance values for water in the borrow ditch vary depending on when water has been added to Pool 4C, but a gradient from high specific-conductance values near the seep to lower values away from the seep has been consistently observed (Erich Gilbert, written commun., 1994). Selenium concentrations in sediment near the seep are elevated (9-20 μg/g) and decrease to about 1 μg/g 700 ft away from the seep (Zhang and Moore, in press, b). The extent of the impact appears to be limited, probably because the discharge of the seep is relatively small.

If the alfalfa in the north field reduces recharge to the saline seep, an accompanying decrease in dissolved-solids concentrations in ground water salinity also may occur. Specific conductance measured in June 1991 during ground-water-quality sampling provide the only pre-remediation data, but these data might not be comparable to subsequent data collected by the USFWS because different meters were used. USFWS personnel measured the specific conductance in water from wells at the study site between spring 1993 and summer 1995 to determine whether water quality improved. Specific conductance was measured in selected bails as each well was purged with a bailer. During a purging episode, typically all water in the well was removed, and another purging episode was initiated after the well had recovered at least partially. The number of bailing episodes required to obtain stable specific-conductance values varied for each well. Figure 12 displays specific-conductance values for water in selected bails collected during successive bailing episodes over several days. Well W-17 required three to four purging episodes to obtain stable specific-conductance values whereas well W-14 had stable readings after two bailing episodes. Figure 13 displays the specific conductance of the water from successive casing volumes as well W-2 was purged during different seasons. The initial specific-conductance value varied significantly on different dates. These data (figs. 12 and 13) illustrate the importance of purging wells adequately to ensure that water sampled from a well is representative of formation water.

Changes in dissolved-solids concentrations in ground water can be detected through repeated measurements of specific conductance. Figure 14 displays specific-conductance data collected from selected test wells over a 29-month period during 1993-95. The data indicate in a very general sense that specific-conductance values may be increasing in wells W-7 and W-13, decreasing in wells W-2 and W-14, and relatively constant in wells W-3 and W-17. Unlike the water-level data (fig. 10), no consistent trends are evident in either the group of wells near the seep or the group of wells near the recharge area. Although seasonal trends are observed during the 29 months, this monitoring period probably is too short to detect long-term trends. Definitive long-term trends may become evident with continued monitoring.

HYDROLOGY AND WATER CHEMISTRY OF STREAMFLOW

Tributaries

Tributaries to Lake Creek and Benton Lake primarily are ephemeral, flowing only in response to snowmelt or heavy or prolonged rainfall. Some tributaries, such as the tributary to Benton Lake (Pool 4) at mouth (site S-8), have intermittent flow. Measured streamflow in tributaries was 0.3 ft^3/s or less except during March 1993 snowmelt and June 1996 precipitation runoff. Streamflow in many tributaries was less than 0.1 ft^3/s. Tributaries frequently were dry when visited. During snowmelt or heavy or prolonged rainfall, streamflow was presumably greater, but few streamflow measurements are available to characterize these infrequent periods.

Two tributary sampling sites have perennial flow that is maintained by subsurface drainage from nonirrigated crop-fallow farmland. Flow is maintained at site S-12 by a tile-drain system installed more than 20 years ago beneath farmland in sec. 18, T. 22 N., R. 2 E., and at site S-14 by a recently installed subsurface agricultural drainage system. Flow in these tributaries is continuous, except possibly during freezing conditions in winter.

Water in basin tributaries was saline. Specific-conductance values in 28 samples from 9 sites on 7 tributaries (including Lake Creek near Interstate 15, site S-15) were high, ranging from 2,190 to 15,000 μS/cm. Only four samples had values less than 6,840 μS/cm—a snowmelt sample from site S-8 and precipitation-runoff samples from sites S-11, S-13, and S-15. Only selected samples from four tributaries were analyzed for major ions. Magnesium, sodium, and sulfate were the predominant ions in samples from three sites (S-8, S-11, and S-12). Samples from site S-14 were

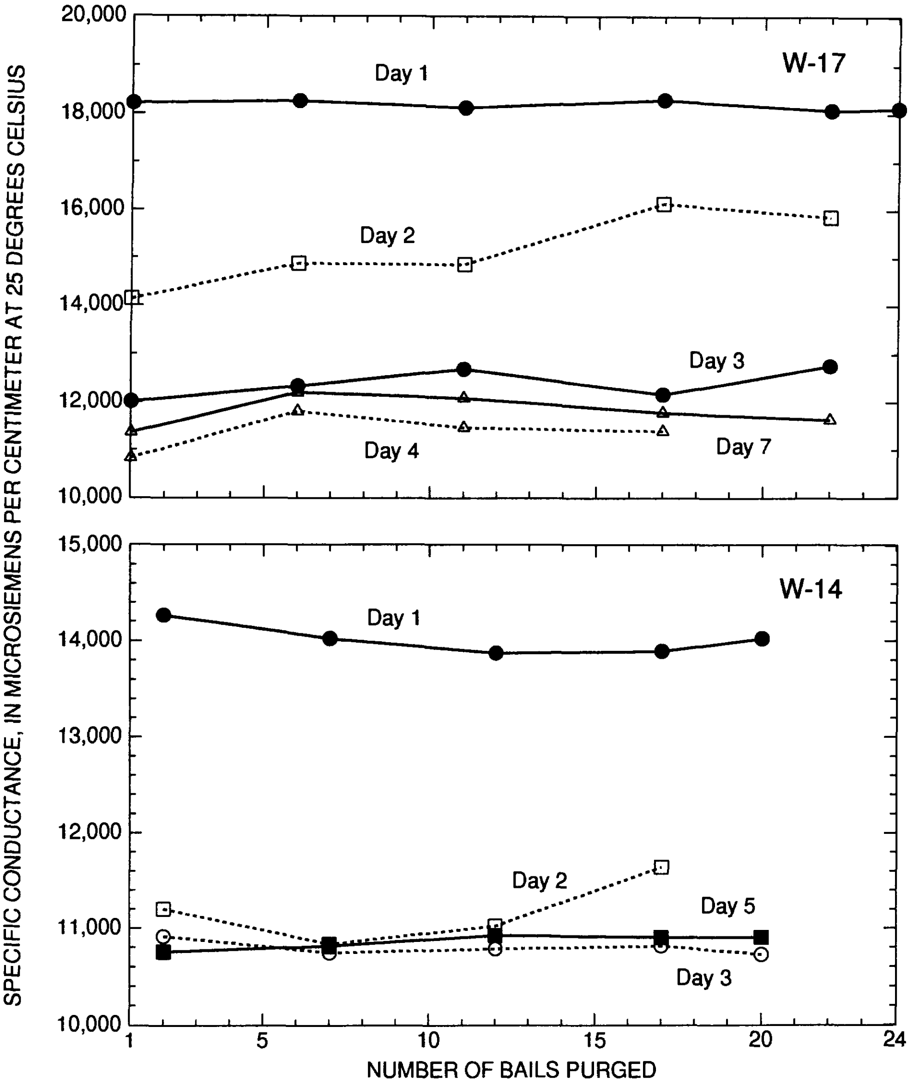


Figure 12. Specific conductance of water withdrawn from wells over several days while being purged with a bailer, Benton Lake saline-seep study site, west-central Montana. Purging started September 27, 1993, in well W-14 and April 5, 1994, in well W-17. Data from Shannon B. Heath (U.S. Fish and Wildlife Service, written commun., 1995).

calcium-sodium sulfate-chloride type water. The reason for the different water type at site S-14 is unknown. Major-ion chemistry in unsampled tributaries is assumed to be similar to the magnesium-sodium sulfate type water found at sites S-8, S-11, and S-12.

Selenium concentrations in tributaries varied significantly. Concentrations in 11 samples from the two perennial tributary sites (S-12 and S-14) that receive water from agricultural drainage systems were very high, ranging from 570 to 3,000 μg/L. Concentrations in 18 samples from 7 sites on the other 5 ephemeral tributaries were much lower, ranging from <1 to 32 μg/L.

Although the selenium in surface water in the basin is assumed to be derived from weathering of seleniferous shale either directly by oxidation of pyrite or organic sulfur in shale or through the dissolution of magnesium-sodium sulfate salts, selenium concentrations in water samples from tributaries do not correlate with major-ion concentrations, such as sulfate, or with specific conductance (fig. 15). Although samples from the three sites with the highest selenium concentrations (seeps at S-3 and tributaries at S-12 and S-14; table 17) were acidic, selenium concentrations in these samples do not correlate with pH (fig. 15), indicating that other geochemical reactions occur between the initial release of selenium, acid, and other oxidation products and the introduction of selenium into tributaries. Samples from two sites (S-11 and S-13) were acidic but had low concentrations of selenium. Selenium concentrations

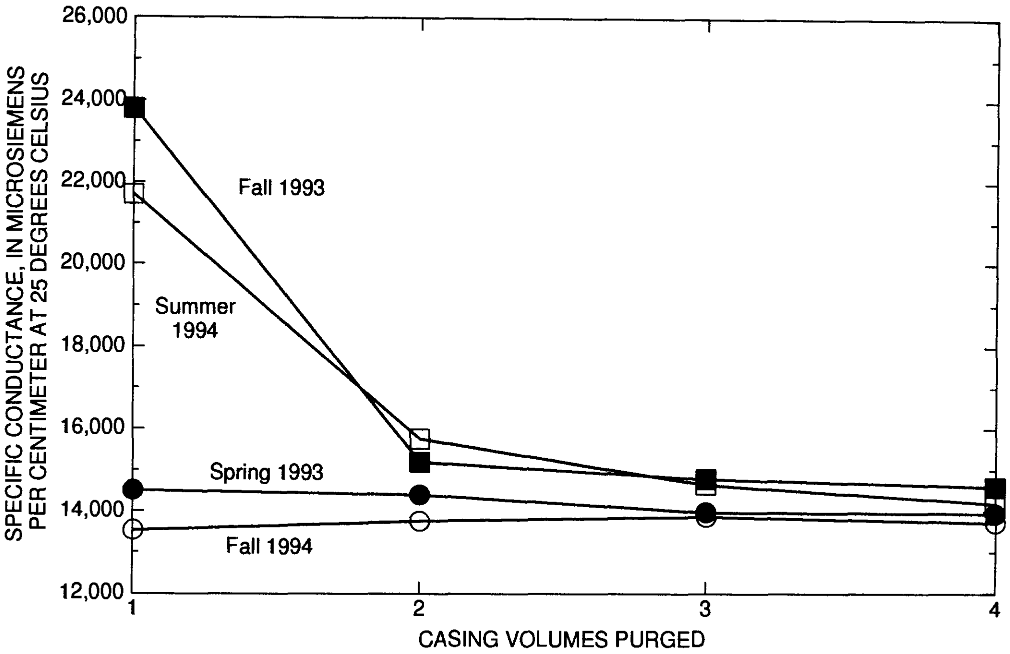


Figure 13. Specific conductance of water purged from well W-2 in successive casing volumes during different seasonal monitoring periods, Benton Lake saline-seep study site, west-central Montana. Data from Shannon B. Heath (U.S. Fish and Wildlife Service, written commun., 1995).

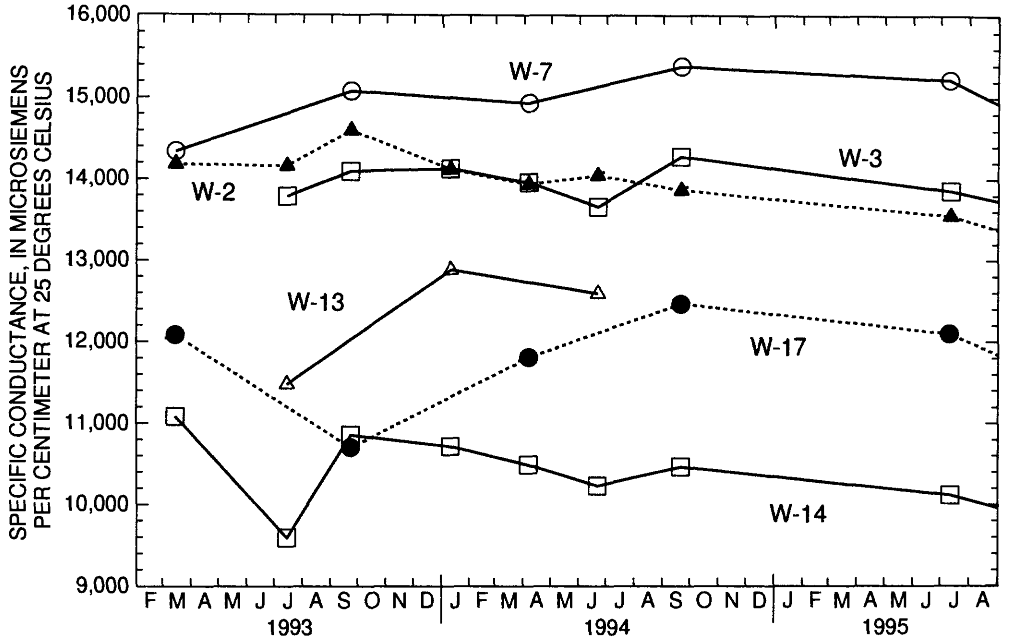


Figure 14. Specific conductance of water samples from selected wells at the Benton Lake saline-seep study site, west-central Montana. Wells were purged 3-5 times before specific conductance was measured. Wells W-2, W-3, and W-7 are near the discharge area of the seep. Wells W-13, W-14, and W-17 are near the recharge area of the seep. Data from Shannon B. Heath (U.S. Fish and Wildlife Service, written commun., 1995).

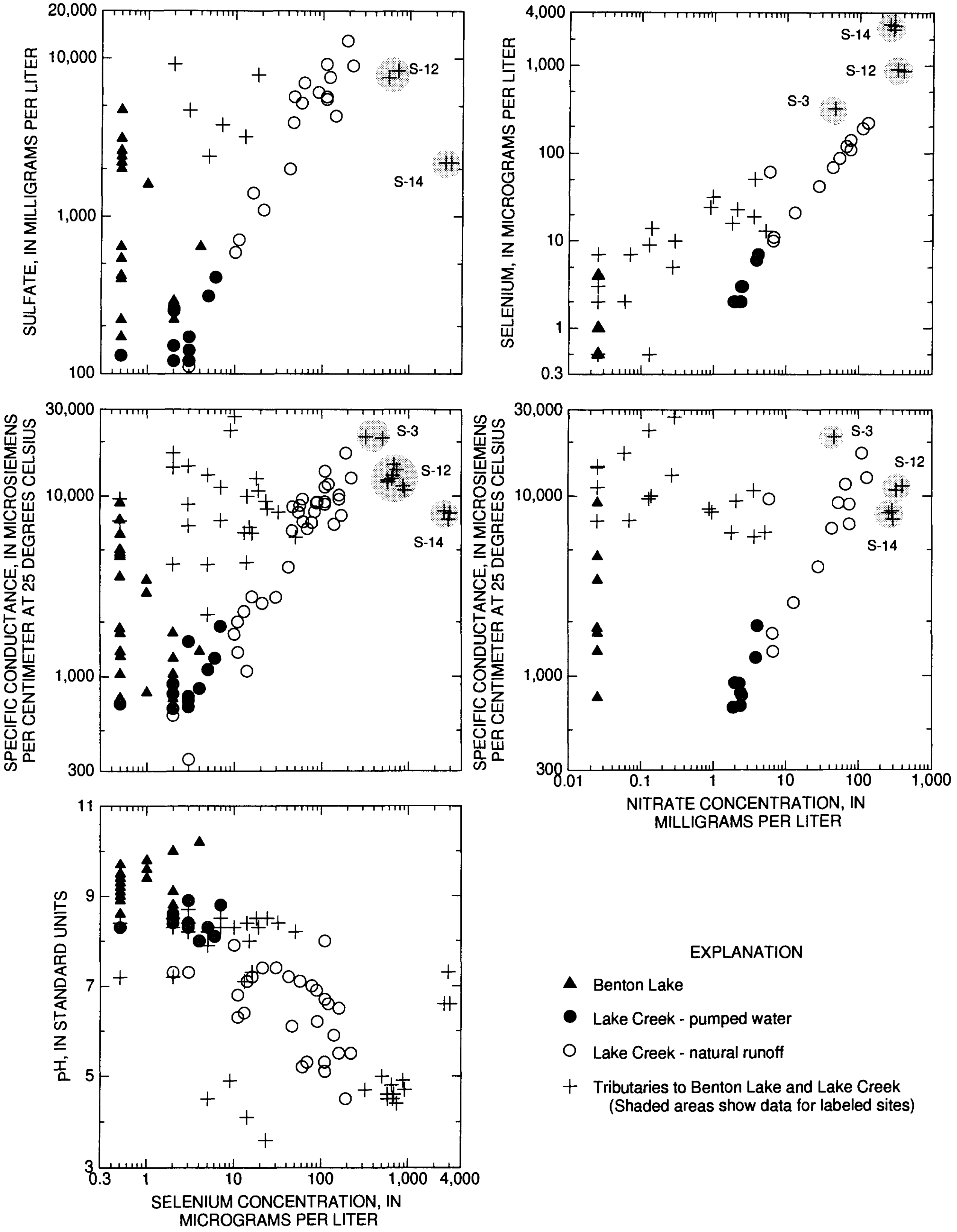


Figure 15. Comparison of chemical characteristics of water samples from Benton Lake, Lake Creek, and tributaries to Lake Creek and Benton Lake, Montana. Concentrations of selenium and nitrate below the minimum reporting level of 1 microgram per liter and 0.05 milligram per liter, respectively, are plotted arbitrarily as 0.5 microgram per liter and 0.025 milligram per liter, respectively.

vary proportionately with nitrate concentrations (fig. 15), indicating that selenium mobilization in the basin might be associated with agriculture. This relation is reasonable because the nitrate and selenium are thought to originate from dryland farming (Kreitler and Jones, 1975; Custer, 1975; Nimick and others, 1996). In addition, both constituents are mobile where geochemical conditions are oxidizing and are removed from solution where conditions are reducing.

Lake Creek

Lake Creek is the major tributary to Benton Lake. The drainage area of Lake Creek is 74.9 mi^2 at the streamflow-gaging station (site S-1) and 96.0 mi^2 at its mouth, compared to about 146 mi^2 for the entire Benton Lake basin.

Streamflow

Streamflow in Lake Creek was monitored continuously during the ice-free season (March or April through October or November) between the installation of the gage in July 1990 and September 1995 (site S-1, fig. 2). Streamflow at the gage consists of natural runoff and water pumped from Muddy Creek (fig. 16). Water from Muddy Creek is diverted at the pump station (site S-17) and transported about 5 mi through a pipeline over a 200-ft drainage divide to a tributary of Lake Creek (site S-16) approximately 11 mi upstream from Benton Lake. Water pumped from Muddy Creek is primarily irrigation drainage from the Greenfields Bench. Records maintained at Benton Lake NWR of electrical use for the pumps enabled segregation of natural-flow and pumped-flow periods. Occasionally, flow was a mixture of pumped water and natural runoff.

During 1991-92 and 1994-95, when precipitation was below or near normal, most (81-98 percent) of the streamflow in Lake Creek was pumped from Muddy Creek (table 3). Relatively large volumes of water were pumped to the refuge to supplement the minimal natural runoff in these years. Precipitation in 1993 was above normal, and natural runoff in Lake Creek was greater than in the drier years. Therefore, the amount of pumped water was reduced in 1993.

Lake Creek is an intermittent stream. Natural streamflow from March through June is generally about 0.1 ft^3/s, except during periods of snowmelt and intense precipitation. Base flow during the spring appears to be derived from very shallow ground water that was recharged since the previous fall. If it occurs, snowmelt runoff is generally in March, as it was in 1993 and 1994. Snowmelt runoff did not occur in 1991 or 1992. The volume of snowmelt runoff (<10 acre-ft) in 1995 was minimal. The largest daily mean discharge at the gage during 1990-95 was an estimated 300 ft^3/s during snowmelt runoff on March 6, 1993. In the spring and early summer, rainstorms generally cause increased flow for several days. Except in 1992, one or more periods of flow greater than 6 ft^3/s occurred in April-June in response to spring rain. Two rainstorms in June 1991 and three in spring 1995 augmented the pumped water flowing in Lake Creek. During July and August, Lake Creek is normally dry except when summer thunderstorms cause brief periods of flow, as occurred in July 1993. Without pumped water, the stream probably would be dry in September and October. However, low flows are sustained in most years during the fall for 1 to 2 months after late summer pumping is stopped, probably in response to bank-storage discharge. Little or no flow occurs from November through February when ponded water is frozen in the channel.

Streamflow in Lake Creek during periods of pumping generally ranged from 30 to 42 ft^3/s when the three pumps at the pump station on Muddy Creek were operated. Occasionally and for short periods of time, only one or two of the three pumps were operated and pumped streamflow was less. The full capacity of the three pumps is utilized only when streamflow in Muddy Creek is augmented sufficiently by irrigation drainage. This condition occurs generally between mid-May and October of most years. When irrigation water is restricted and irrigation drainage to Muddy Creek is reduced, such as occurred in summer 1994, the pumps operate intermittently and less water is pumped. Water commonly is pumped in the spring between mid-April and mid-June to raise water levels in Benton Lake to levels optimum for water-bird reproduction. The pumps generally are not operated between mid-June and mid- to late-August to prevent outbreaks of avian botulism. Typically, water is pumped again from late-August through October to provide water for the fall migration of water birds and to store water for the next spring. Water is pumped only if natural runoff has not provided adequate water and if funds are available for electricity to operate the pumps.

Water Quality

Water quality in Lake Creek is variable, depending on whether streamflow is derived from pumped water, overland runoff during high-flow conditions, or runoff during base-flow conditions sustained by ground-water discharge. The continuous record of specific conductance provides a general indication of

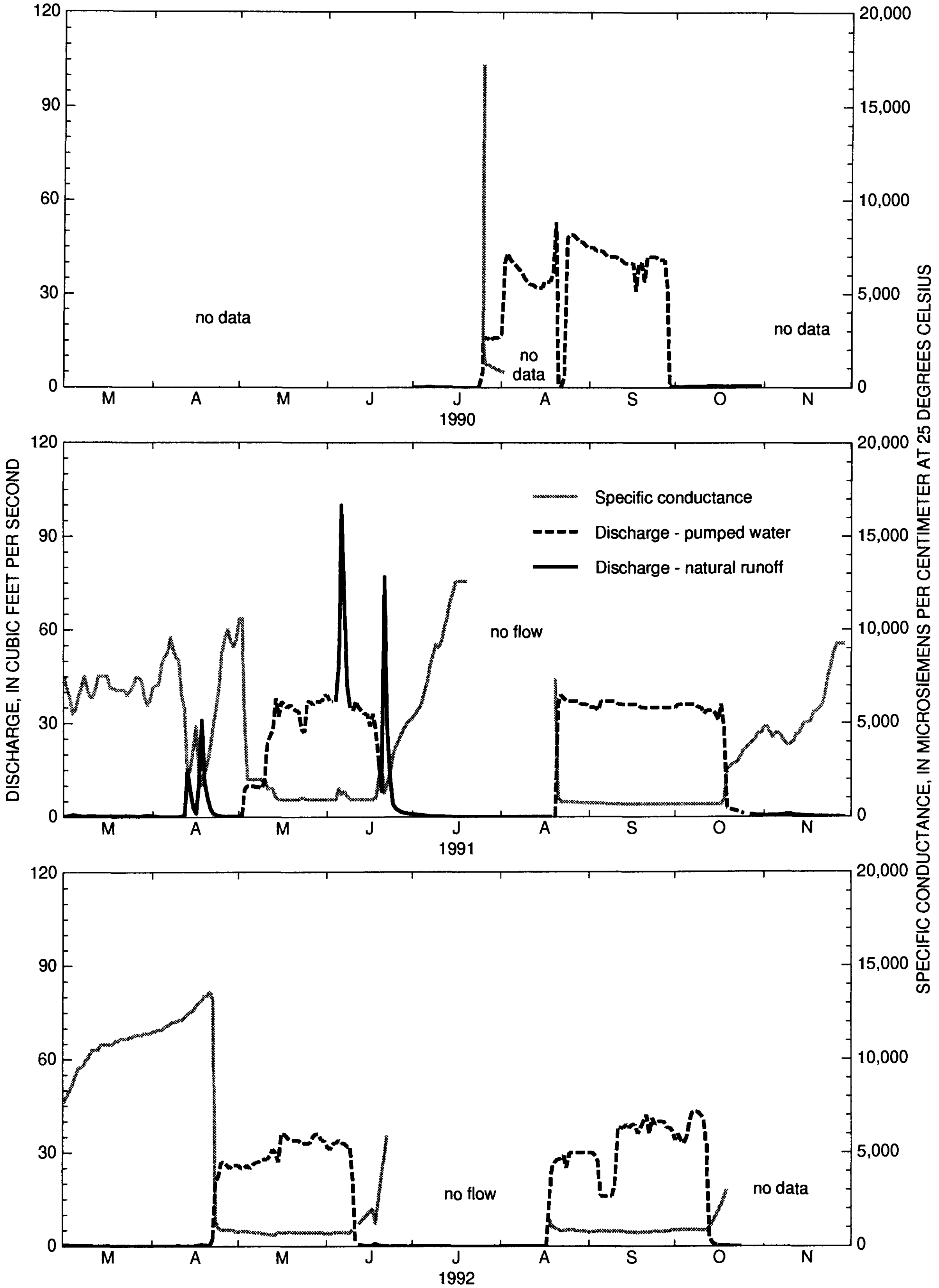


Figure 16. Continuous record of discharge and specific conductance, Lake Creek (site S-1, fig. 2), Montana.

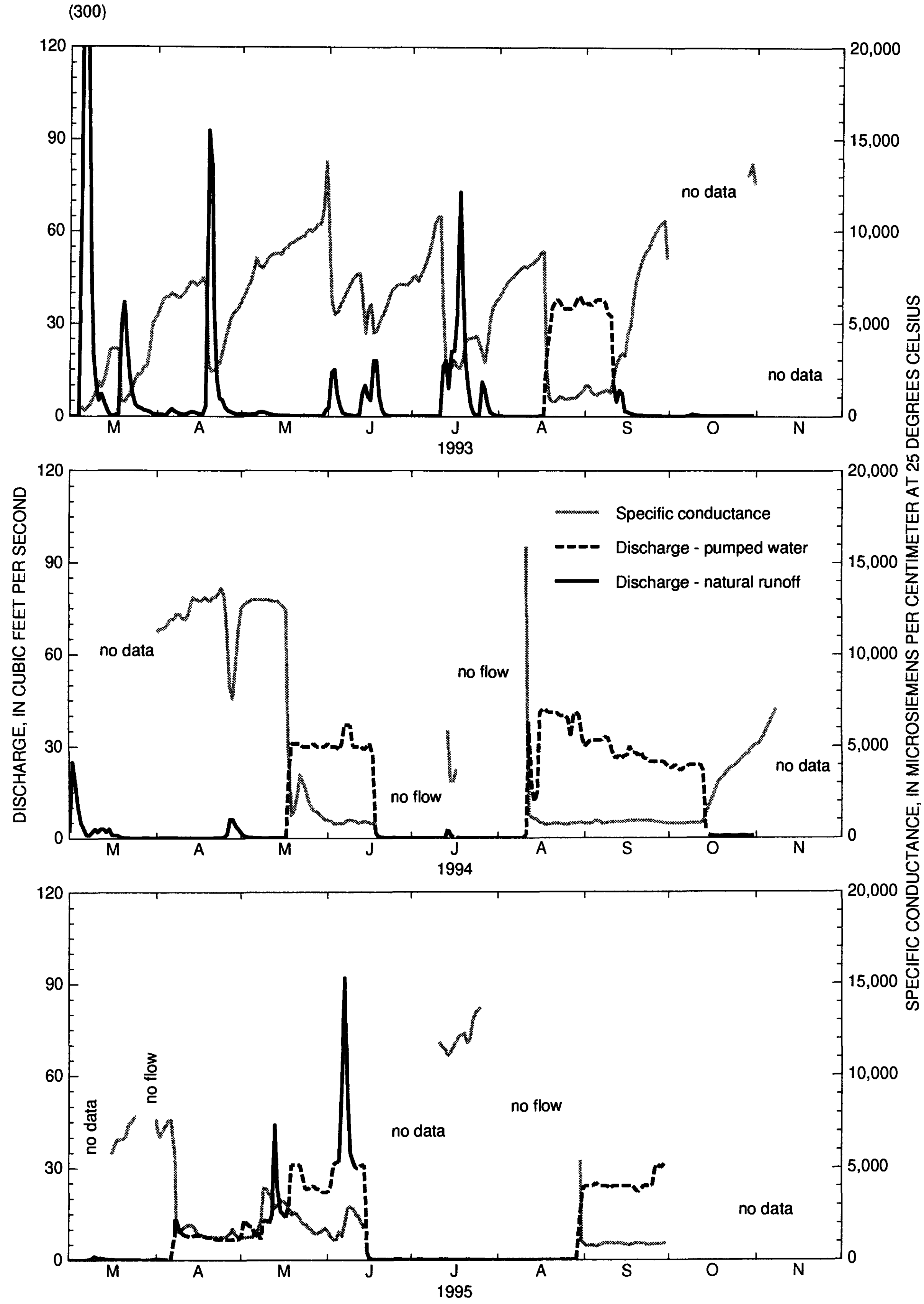


Figure 16. Continuous record of discharge and specific conductance, Lake Creek (site S-1, fig. 2), Montana. (Continued)

Table 3. Annual volume of pumped water and natural runoff in the Benton Lake basin, Montana, 1991-95

Water year	Pumped water[1] (acre-feet)	Pumped water[1] Percent of total	Natural runoff: Lake Creek[1] (acre-feet)	Natural runoff: Remainder of basin[2] (acre-feet)	Natural runoff: Combined (acre-feet)	Natural runoff: Percent of total	Total (acre-feet)
1991	5,782	81	721	600	1,321	19	7,103
1992	6,892	98	89	74	163	2	7,055
1993	2,552	32	3,011	2,503	5,514	68	8,066
1994	4,948	91	280	233	513	9	5,461
1995	4,464	87	369	307	676	13	5,140
Mean	4,928	75	894	743	1,637	25	6,565
Total	24,638	75	4,470	3,717	8,187	25	32,825

[1] Measured at Lake Creek gage (site S-1, fig. 2). During periods when flow in Lake Creek was a mixture of natural runoff and pumped water, flow was apportioned between the two sources on the basis of pumping and precipitation records.

[2] Extrapolated from volume measured at Lake Creek gage on the basis of relative size of drainage areas.

water-quality trends in Lake Creek (fig. 16). Typically, specific-conductance values are high when streamflow is low and are low when streamflow is high. When large volumes of runoff or pumped water flow into Lake Creek, specific conductance changes rapidly. Often, the initial flush of water down a dry channel dissolves accumulated salts and creates very high specific-conductance values (measured as high as 26,100 µS/cm, table 18 at back of report) that are short-lived (figs. 6 and 16). Because the runoff or pumped water generally has low specific conductance, and because the surface salts are rapidly depleted, the conductance of streamflow drops rapidly from the initially high value owing to both dilution and loss of a salt source. As flow recedes, specific-conductance values gradually increase until flow ceases or more water from pumping or runoff is introduced. These patterns are particularly evident for spring to fall of 1993, a period of numerous rainstorms. During low flow (3 ft^3/s or less), specific-conductance values ranged from 2,740 to 14,000 µS/cm. Snowmelt runoff, which commonly occurs over frozen soil, can have the lowest specific-conductance values; on March 6, 1993, the mean daily value was 322 µS/cm. Specific-conductance values of pumped water ranged from about 600 to 2,000 µS/cm. Precipitation runoff has higher specific-conductance values than snowmelt runoff, presumably because of flushing of salt crusts and deeper leaching of unfrozen soil. Minimum values during peak flow in precipitation runoff are typically between 2,500 and 5,000 µS/cm.

The quality of water in Lake Creek was determined from data for water samples collected in 1986-95 (table 18). The water samples can be divided into three groups. The two major groups are pumped water and natural runoff. The third group includes samples collected in July 1990 and August 1995 when pumped water flowed in a previously dry channel; these samples are not described below, but the July 1990 samples were discussed in the preceding "Saline Seeps" section.

Samples of pumped water were a magnesium bicarbonate type water. Dissolved-solids concentrations ranged from 402 to 694 mg/L, with a median of 489 mg/L. Selenium concentrations ranged from <1 to 10 µg/L, with a median of 3 µg/L. Dissolved and total-recoverable concentrations of selenium were virtually identical (fig. 17). Therefore, no distinction is made between the two phases in this report. In general, the chemistry of pumped water had relatively little variation because the irrigation drainage from which it is derived generally had consistent chemistry.

The continuous data for site S-1 indicate that the specific conductance of pumped water was higher than normal during two periods. The first period was during late August and early September 1993 when increased precipitation runoff in the non-irrigated upper Muddy Creek basin probably caused increased concentrations of major ions and selenium in Muddy Creek and, consequently, the water pumped to Benton Lake. Specific-conductance values ranged from about 900 to 1,600 µS/cm during this period. Higher than normal specific-conductance values ranging from about 1,200 to 2,000 µS/cm in pumped water also occurred during April-June 1995. As in summer 1993, the higher values may have been related to high values in Muddy Creek. Because the pumping rate was reduced during this period, high-conductance water, possibly from natural runoff or released from bank storage, may have caused the increased specific conductance.

Samples of natural runoff in Lake Creek were a magnesium-sodium sulfate type water. Constituent concentrations in natural runoff generally were much higher than in pumped water. The quality of natural runoff varied greatly, because the large flows caused by snowmelt runoff are dilute whereas base flow during warm periods has high constituent concentrations. The first flush of precipitation runoff during the summer also can have high constituent concentrations, owing to dissolution of efflorescent salts that accumulate along ephemeral stream channels in the basin. The early June 1993 runoff is an example (fig. 16). Dissolved-solids concentrations ranged from 198 mg/L in one sample collected during snowmelt conditions in March 1993 to 13,400 mg/L during base flow in April 1992. The median dissolved-solids concentration was 7,810 mg/L.

Natural runoff generally was acidic, with pH values varying from 5.1 to 8.0. Values higher than 7.0 generally were measured only when snowmelt or precipitation runoff caused flows 3 ft^3/s or greater. Values of pH in natural runoff were considerably lower than the pH (range of 8.0-8.9) in pumped water. The low pH indicates that base flow in Lake Creek is derived from ground-water discharge from the Colorado Group shale, either from agriculturally induced drainage (such as sites S-12 and S-14) or from release of bank storage along Lake Creek. In either circumstance, the water quality presumably results from acid produced by oxidation of sulfides in the shale.

Concentrations of trace metals in Lake Creek were high when flow was acidic (Lambing and others, 1994, table 14). In water samples with pH values less than 7, ranges of dissolved concentrations were <1 to 15 µg/L cadmium, 2 to 15 µg/L copper, 59 to 2,000 µg/L nickel, and 100 to 3,500 µg/L zinc. Concentrations of dissolved arsenic were low, ranging from <1 to 2 µg/L.

Selenium concentrations in natural runoff ranged from 2 µg/L during snowmelt runoff to 220 µg/L during base-flow conditions, with a median concentration of 74 µg/L in the 30 samples collected in 1990-95 (table 18). Selenium concentrations in natural runoff in Lake Creek are proportional to specific-conductance values and concentrations of sulfate and nitrate (fig. 15). The data for Lake Creek in each graph fall along a line with a slope close to 1, indicating that the concentrations could be controlled solely by dilution and that selenium in Lake Creek may be supplied largely by one source. Tributaries in the basin have a wide range of selenium concentrations but a relatively narrow range of specific-conductance values. These data signify that all tributaries supply dissolved solids but only a few supply selenium. The graphs of selenium concentration versus specific conductance and sulfate concentration show that natural runoff in Lake Creek could be a mixture of water from the two tributaries (sites S-12 and S-14) having high selenium concentrations and other tributaries having much lower selenium concentrations. The graph comparing concentrations of selenium and nitrate shows that these constituents also vary proportionally along a 1:1 dilution line. Samples from site S-12 plot on the extension of this line, indicating that this drain may be the major source of selenium and nitrate in Lake Creek.

The quality of natural runoff during base flow in the Benton Lake basin is controlled primarily by the quality of shallow ground water as opposed to deep ground water, which probably is isolated from the shallow system. The connection between shallow ground water and surface runoff is apparent when comparing water-quality characteristics. Major-ion composition, pH values, and concentrations of dissolved solids, nitrate, and selenium (tables 16-18) as well as ratios of stable isotopes (fig. 11) are similar in shallow ground water and natural runoff in the basin.

Chemical data for the periodic water samples collected during the study provide some indication of the typical water quality through time and over a range of hydrologic conditions. Discharge-weighted mean concentrations can be calculated to indicate the average quality of water flowing past the gage (table 4) relative to the volume of water. Because transport of chemical constituents is dependent on flow quantity, the estimated discharge-weighted concentrations are more representative than the median values from the periodic water samples, in terms of loading of dissolved solids and selenium to Benton Lake. The discharge-weighted mean concentrations were estimated from the daily specific-conductance and discharge record for March 1991 through September 1995, as described in detail in the next section, "Hydrology and Water Chemistry of Benton Lake."

The median constituent concentrations measured in the 12 samples of pumped water were similar to the estimated discharge-weighted mean concentrations, because the quality of pumped water is relatively constant throughout the year and from year to year. Median concentrations in the 30 samples of natural runoff, however, were substantially different from the discharge-weighted values because of the wide range of water quality in runoff and base flow. For natural runoff, most median concentrations of samples were much higher than the estimated discharge-weighted mean concentrations because many samples were collected during periods of low flow (3 ft^3/s or less). Although constituent concentrations were high, streamflow was low during these periods and the net

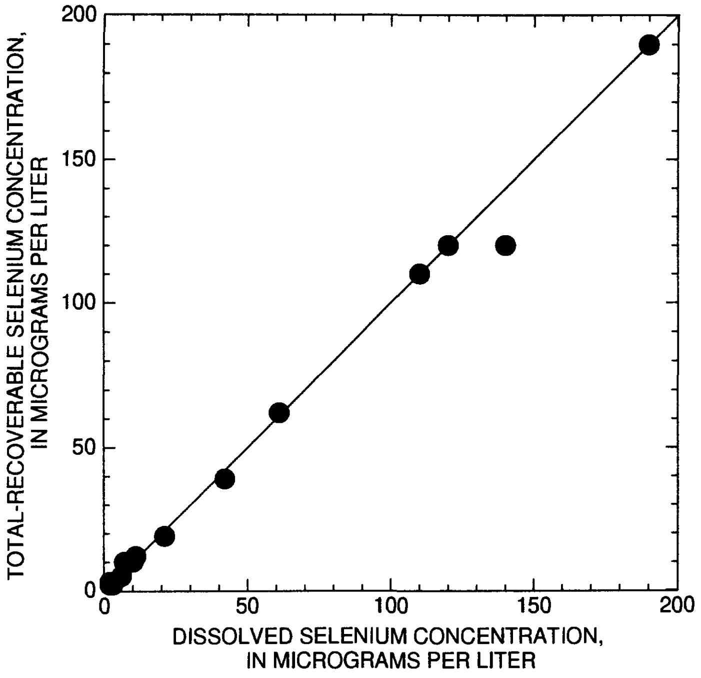


Figure 17. Relation of dissolved and total-recoverable selenium concentrations in water samples from Lake Creek (site S-1, fig. 2), Montana.

Table 4. Typical constituent concentrations in Lake Creek, Montana

[Concentrations are in milligrams per liter unless otherwise indicated. Abbreviations: µg/L, micrograms per liter]

Constituent	Pumped water		Natural runoff	
	Median from water samples	Estimated discharge-weighted mean[1]	Median from water samples	Estimated discharge-weighted mean[1]
Calcium	46	51	260	76
Magnesium	57	68	735	168
Sodium	40	68	1,050	237
Alkalinity	253	246	23	47
Sulfate	150	299	5,450	1,280
Chloride	8.5	12	210	40
Dissolved solids	489	646	7,810	1,780
Selenium (µg/L)	3	5	74	15

[1] Calculated from continuous discharge and specific-conductance data for 1991-95 from the Lake Creek gage (site S-1, fig. 2).

inflow of solutes to Benton Lake was relatively small. Natural flows in Lake Creek are infrequently high but provide large volumes of relatively dilute precipitation or snowmelt runoff to Benton Lake. For natural runoff, the constituent loading to Benton Lake estimated from periodic samples would be much higher than the loading estimated from the daily continuous specific-conductance record.

HYDROLOGY AND WATER CHEMISTRY OF BENTON LAKE

Benton Lake is a closed basin (fig. 2) that receives flow from Lake Creek and other smaller streams. Because Benton Lake has no outlet, all inflowing solutes remain in the lake unless some removal mechanism(s) exists. Removal mechanisms can be different for different solutes. If the dissolved solids are not removed, the dissolved-solids concentrations of this closed-basin lake would increase each year and eventually become sufficiently high to impair the quality of habitat the lake provides for water birds. Whether the dissolved solids delivered each year are removed is one of the key questions that this study attempted to answer.

Hydrology

Water entering Benton Lake is derived from three sources. The first source is precipitation that falls on the lake. The second source is natural runoff to the lake. The third source is pumpage from Muddy Creek, whose flow consists almost entirely of irrigation drainage from the Greenfields Bench (Osborne and others, 1983; Nimick and others, 1996). The amount of water pumped to the refuge from Muddy Creek varies from year to year. The quantity of natural runoff available from the basin determines the need for pumped water and is evaluated annually with respect to achieving optimum water levels and minimizing pumping costs. Managing water at Benton Lake NWR is complex because of the unpredictability of the timing and volume of inflows from natural runoff, the lack of a lake outlet to release excess water, and the varying seasonal needs for water levels necessary to optimize waterfowl habitat.

In most years, the pumped water, natural runoff, and precipitation that flows into or falls on the lake evaporates. Therefore, on average, no net long-term gain or loss in water stored in the lake occurs. Some water might be lost to deep percolation through the lakebed, but due to the thick layer of clay and silty clay underlying the lake, this process, in comparison to evaporation, is not considered to be significant.

The annual volumes of natural runoff to Benton Lake (table 5) were calculated by the USFWS from lake-stage data collected during 1970-94. These data describe runoff from 137 mi^2, an area that includes the entire Benton Lake basin except for the 5,600 acres covered by Benton Lake. These data were collected after periods of runoff and were used in conjunction with stage-capacity curves to calculate total runoff into Benton Lake. Annual volumes of natural runoff from the Benton Lake basin were highly variable, ranging from 0 to 19,200 acre-ft for the 25-year period. Mean annual natural runoff was estimated to be 3,349 acre-ft. The reliability of this long-term estimate was supported by a predictive equation (Omang and Parrett, 1984) applicable to central and eastern Montana that gave a similar estimate of 3,110 acre-ft (Charles Parrett, U.S. Geological Survey, written commun., 1992). However, the median annual natural runoff (1,078 acre-ft) is much less than the mean annual value and probably is more indicative of the typical amount of natural runoff that is likely to occur in any 1 year.

The amount of annual precipitation is one factor that affects the annual volume of natural runoff entering Benton Lake (fig. 18). In most years when annual precipitation (measured near Power or at Benton Lake) was less than about 12 in., annual runoff to Benton Lake was less than 2,000 acre-ft. When annual precipitation was greater than about 17 in., annual runoff generally was greater than 9,000 acre-ft. These statements are generalizations and do not always apply. Other factors such as the amount of winter snowpack, the intensity of rainstorms, and the distribution of precipitation over the basin also affect the volume of runoff. For instance, in 1979, natural runoff was 12,100 acre-ft, the third highest annual value in the 25-year period, but annual precipitation (6.51 in. near Power) was the lowest annual total for the period. The large volume of runoff in 1979 resulted from melting of an exceptionally thick snowpack, most of which accumulated in November and December 1978. In contrast, 1993 was a wet year but natural runoff was relatively low—only 3,049 acre-ft. This low runoff value is an anomaly when compared to the annual precipitation near Power of 21.49 in., the second highest total recorded in the 25-year period. The 1993 runoff total, however, seems more reasonable when compared to annual precipitation (17.81 in.) recorded at the refuge headquarters. In 4 other years between 1975 and 1994, when annual precipitation was 15-17 in. at Benton Lake, the corresponding annual runoff was 1,100-4,132 acre-ft.

Table 5. Annual volume of natural runoff and pumped water entering Benton Lake and annual precipitation at Benton Lake and Power, Montana, 1970-94

[Symbol: --, no data]

Calendar year	Inflow to Benton Lake (acre-feet)		Annual precipitation (inches)	
	Pumped water[1]	Natural runoff[1]	Power[2]	Benton Lake National Wildlife Refuge[1]
1970	3,670	3,000	12.78	--
1971	6,371	0	8.69	--
1972	9,079	990	9.75	--
1973	6,643	0	7.59	--
1974	5,897	334	10.30	--
1975	0	13,933	21.60	19.46
1976	2,978	400	10.19	11.58
1977	4,167	0	11.81	13.02
1978	0	19,200	18.99	21.71
1979	68	12,100	6.51	9.03
1980	2,000	1,100	10.60	16.66
1981	3,650	--	13.13	13.83
1982	3,037	4,132	10.47	16.11
1983	2,822	1,763	12.04	15.22
1984	4,790	1,947	8.25	10.11
1985	6,380	1,157	15.11	16.90
1986	3,376	4,759	11.10	11.59
1987	7,987	350	10.25	11.52
1988	7,517	208	8.49	8.36
1989	212	9,710	17.42	21.16
1990	4,797	1,056	9.12	11.30
1991	8,028	943	13.00	12.93
1992	7,276	21	12.14	10.43
1993	1,932	3,049	21.49	17.81
1994	5,800	227	7.52	9.00
Mean	4,339	3,349	[3]11.93	13.89
Median	4,167	1,078	[4]10.60	12.98

[1] Data compiled from unpublished annual water-use reports for Benton Lake National Wildlife Refuge (Stephen J. Martin, written commun., 1994, 1995).

[2] Data from National Oceanic and Atmospheric Administration (issued annually).

[3] Mean for 1975-94 was 12.48.

[4] Median for 1975-94 was 11.46.

Annual volumes of pumped water ranged from 0 to 9,079 acre-ft in 1970-94 (table 5). More than 1,900 acre-ft was pumped every year except in the 4 years with the highest natural runoff. Less than 212 acre-ft water were pumped in each of those 4 years. The values of mean (4,339 acre-ft) and median (4,167 acre-ft) volume of annual pumped water are almost equal, indicating that the volume of pumped water does not vary from year to year nearly as much as does the annual volume of natural runoff.

On the basis of the 1970-94 estimates of 3,349 acre-ft of natural runoff and 4,339 acre-ft of pumped water from Muddy Creek, long-term mean annual inflow to Benton Lake is 7,688 acre-ft. During this 25-year period, about 56 percent of the total cumulative inflow to Benton Lake was pumped water. For any given year, however, the amount of pumped water flowing to Benton Lake (median value = 4,167 acre ft) is likely to be much greater than the amount of natural runoff (median value = 1,078 acre-ft).

During 1991-95, the total volume of natural runoff was below average and the volume of pumped water was above average (table 3). The mean annual natural runoff was 1,637 acre-ft, which represents only 49 percent of the long-term (1970-94) mean. During 1991-95, the mean annual volume of pumped water was 4,928 acre-ft, compared to the long-term mean annual estimate of 4,339 acre-ft. The mean annual volume of water pumped during the study period, therefore, was about 114 percent of normal.

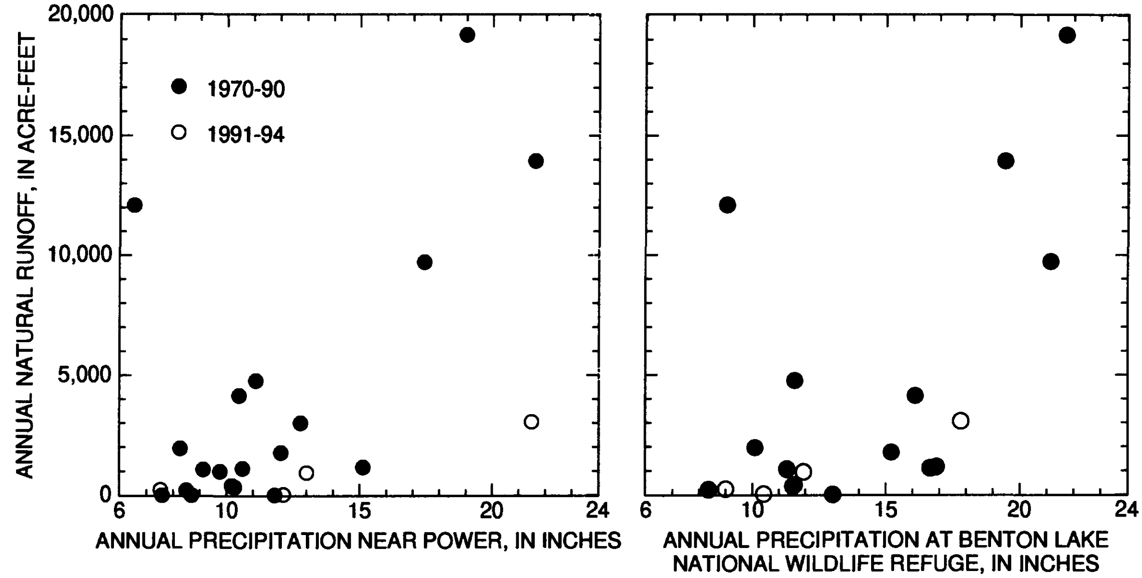


Figure 18. Relation of annual natural runoff to Benton Lake and annual precipitation near Power and at Benton Lake National Wildlife Refuge, Montana. Precipitation data near Power from National Oceanic and Atmospheric Administration (issued annually). Runoff and precipitation data at Benton Lake National Wildlife Refuge from Stephen J. Martin (Benton Lake National Wildlife Refuge, written commun., 1994, 1995).

Loading of Major Ions, Dissolved Solids, and Selenium

Quantifying the loads of major ions and selenium delivered to Benton Lake is important, because these solutes have the potential to accumulate and create a biological hazard in the lake. Constituent loads first were determined for the Lake Creek gage site (S-1) from daily mean streamflow and specific-conductance data and relations between specific conductance and constituent concentrations. Specific conductance was used as a substitute for dissolved-solids and selenium concentrations because it is easier to measure and because the correlations between specific conductance and constituent concentrations were good. Loads contributed by natural runoff from the entire basin were estimated from loads in natural runoff measured at the Lake Creek gage extrapolated to the entire basin based on relative drainage-area size. The ungaged part of the basin is 62 mi^2, or 45 percent of the basin excluding Benton Lake. This estimate of total basin load from natural runoff was added to the loads estimated for pumped water measured at the gage to derive an estimate of average annual inflow to Benton Lake.

Constituent loads transported past the Lake Creek gage site (S-1) were quantified for the period March 1991 through September 1995 using a multistep procedure. First, relations between individual constituent concentrations and specific conductance were developed using linear regressions of data for samples collected during the study period. For major ions and dissolved solids, separate relations were developed for pumped water and for natural runoff (figs. 19-21). Potassium was omitted from this analysis because measured concentrations were much lower than concentrations of the other major cations. The relation between specific conductance and selenium was not dependent on the source of water and only one relation was developed (fig. 22). In this case, the relation was linear for log-transformed values of specific conductance and selenium concentration. The next step in calculating constituent loads was to compute, using the appropriate relation for pumped or natural flow, daily mean concentrations for each major ion, dissolved solids, and selenium from the daily mean value of specific conductance. Then, the daily mean concentrations were combined with daily mean discharge to compute daily mean loads of each constituent. Next, the daily load values were summed to determine the annual load of each constituent in pumped water and natural runoff. To determine discharge-weighted mean concentrations in Lake Creek for 1991-95 (table 4), the total load of

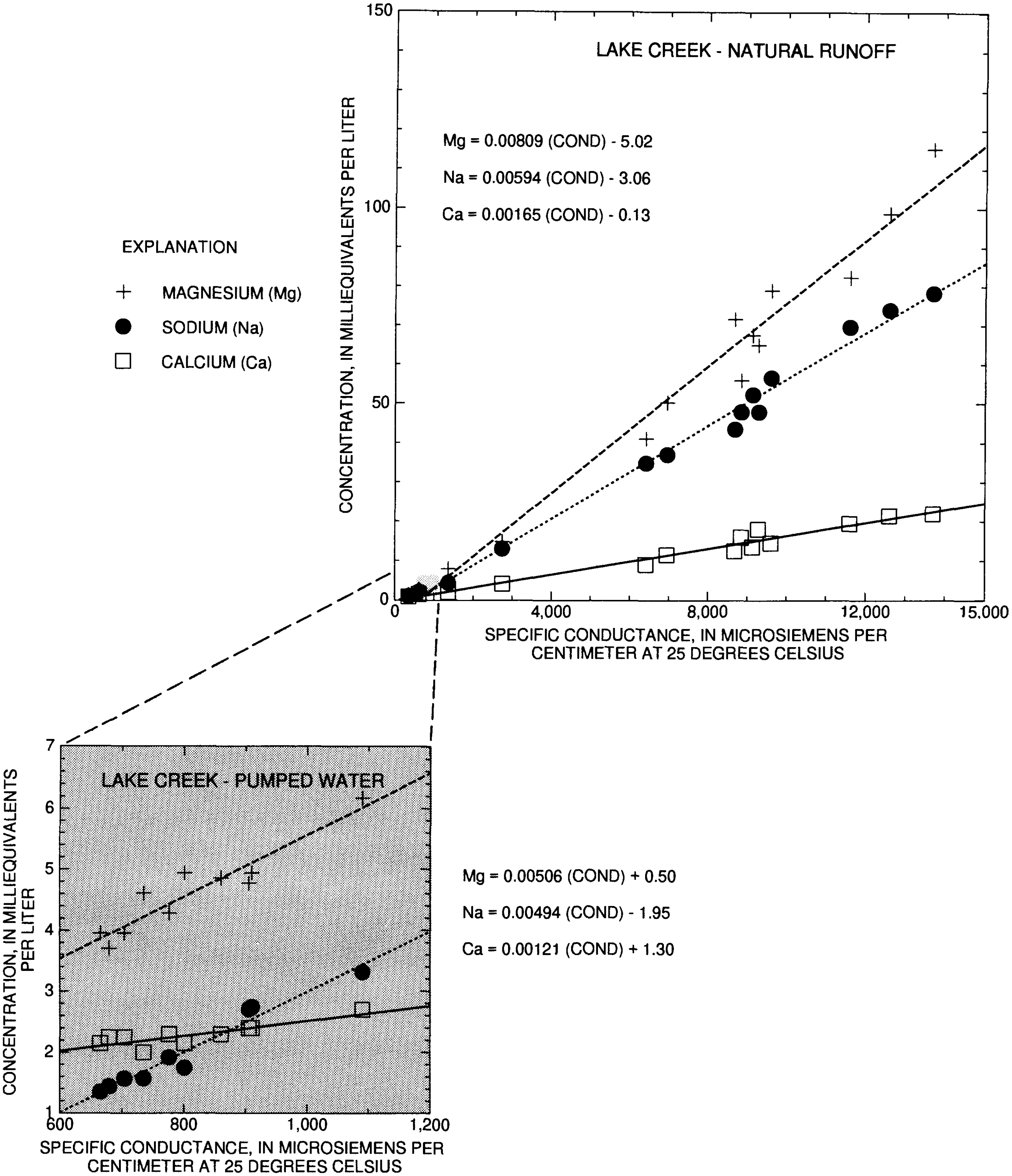


Figure 19. Relation of cation concentrations and specific-conductance (COND) values in samples of pumped water and natural runoff collected from Lake Creek (site S-1, fig. 2), Montana.

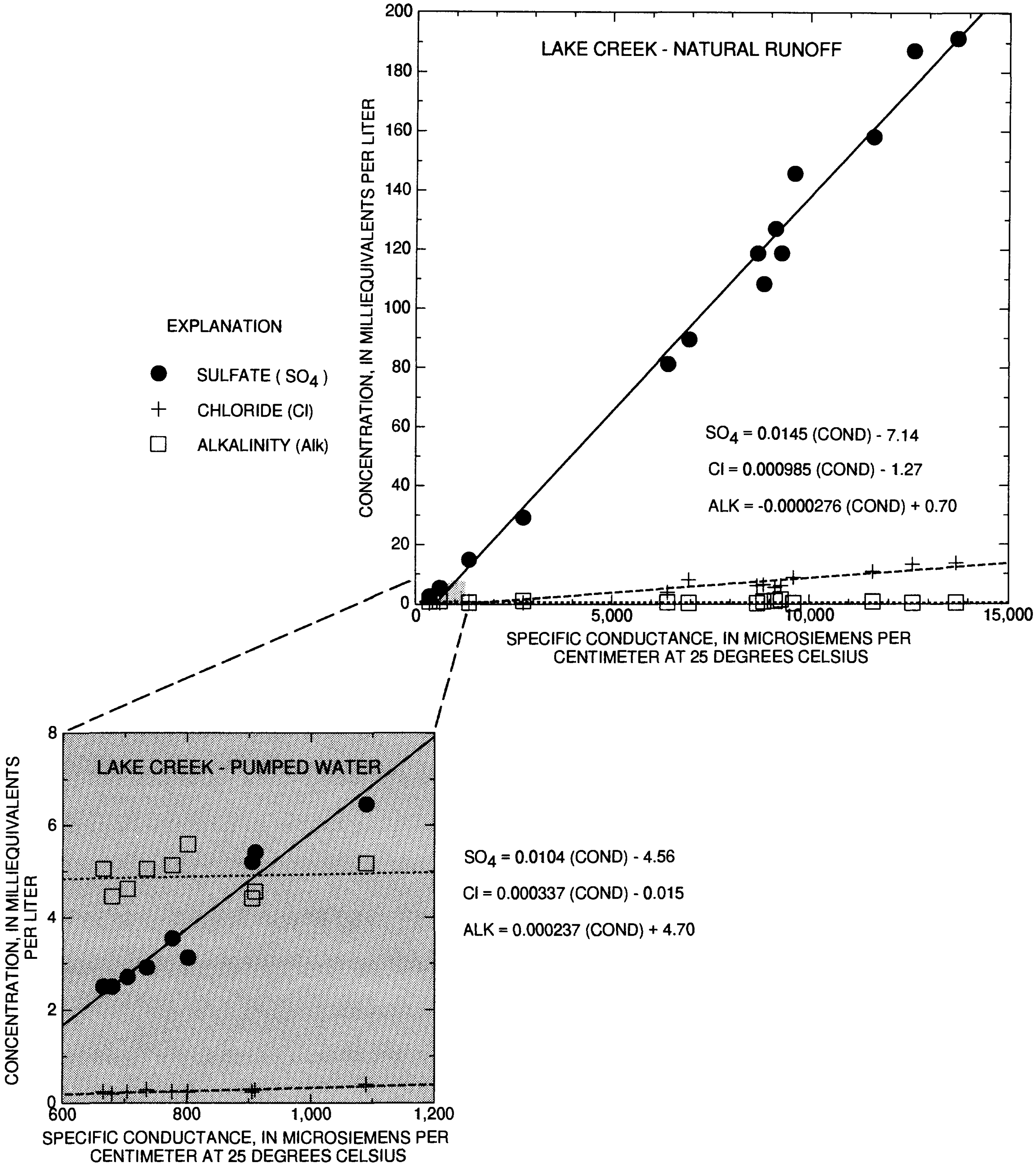


Figure 20. Relation of anion concentrations and specific-conductance (COND) values in samples of pumped water and natural runoff collected from Lake Creek (site S-1, fig. 2), Montana.

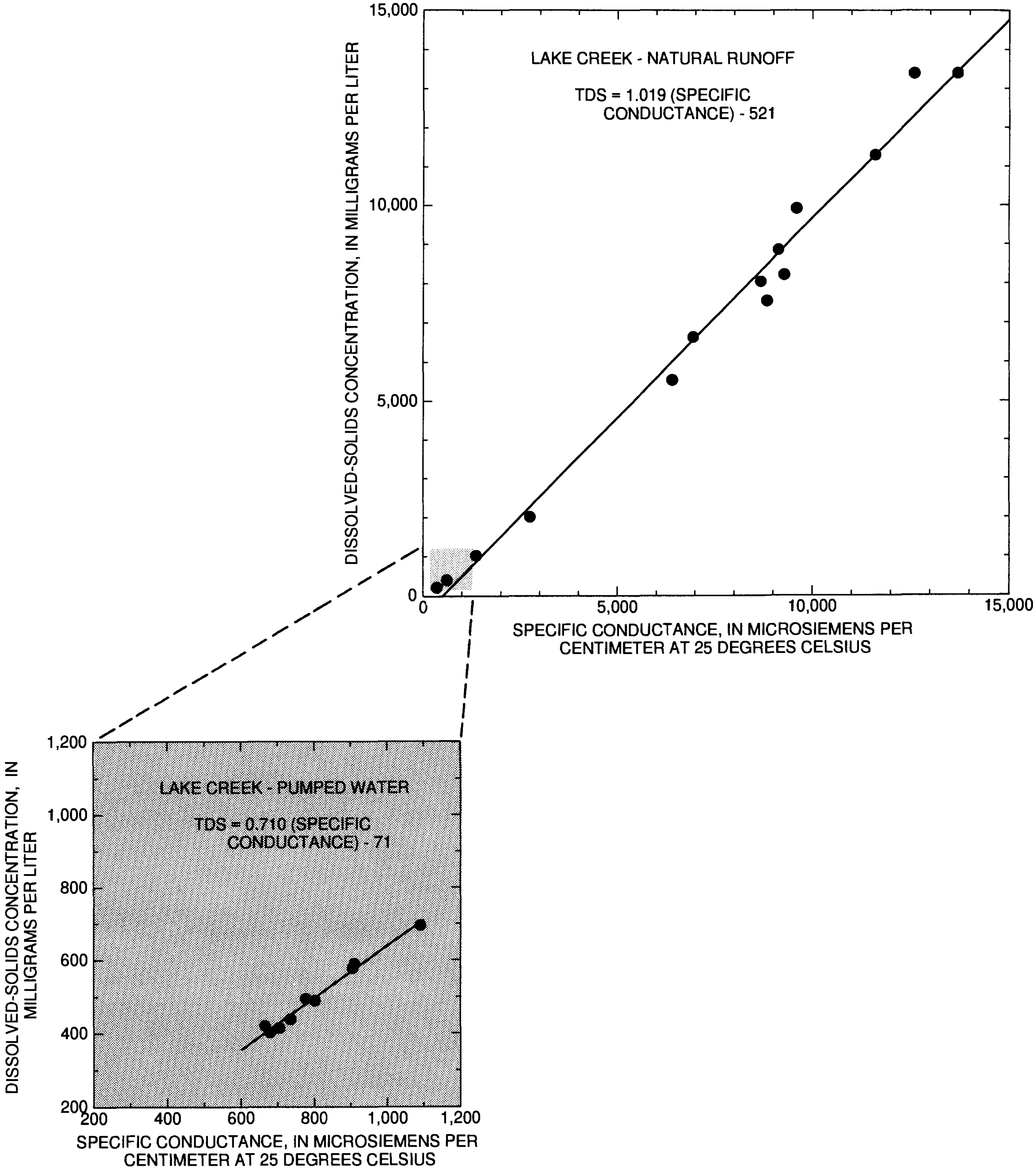


Figure 21. Relation of dissolved-solids (TDS) concentrations and specific-conductance (COND) values in samples of pumped water and natural runoff collected from Lake Creek (site S-1, fig. 2), Montana.

the total volume of either pumped water or natural runoff (as appropriate).

The total dissolved-solids load to Benton Lake during the 1991-95 water years was 41,416 tons (table 6); the mean annual load was 8,283 tons. Annual totals in 1991-92 and 1994-95 ranged from 5,440 to 7,510 tons. Most (60-79 percent) of the dissolved solids was derived from pumped water in 1991-92 and 1994-95. In 1993, when precipitation was above normal, the annual dissolved-solids load (15,109 tons) was higher and the proportion (16 percent) derived from pumped water was substantially less.

Mean annual dissolved-solids loads were estimated for long-term natural runoff and pumped water data for 1970-94 (table 5) and the estimated discharge-weighted concentrations determined above for 1991-95. The mean annual dissolved-solids load (4,329 tons) of pumped water during 1991-95 was greater than the long-term mean annual pumped load (3,812 tons) because of increased pumping during 1991-95. The estimated long-term mean annual dissolved-solids load from natural flow (8,106 tons) is substantially larger than the mean load (3,954 tons) transported to Benton Lake during 1991-95, because natural runoff was below average during 1991-95. The long-term proportion of total annual dissolved-solids load contributed to Benton Lake by natural runoff is 68 percent, compared to 48 percent contributed during the study period. Although pumped water provided most of the dissolved solids in 4 of the 5 years during 1991-95, natural runoff is the major contributor of dissolved solids to Benton Lake.

Annual loads of major ions are listed in table 7. In 1991-92 and 1994-95, pumped water contributed 48-100 percent of the load of each major ion. In 1993, pumped water provided only 9-22 percent of the load of each major ion except alkalinity, for which pumped water supplied 75 percent of the load. The relative proportions of anions (particularly alkalinity versus sulfate plus chloride) are important because the evaporative salts produced from alkalinity are less soluble than the

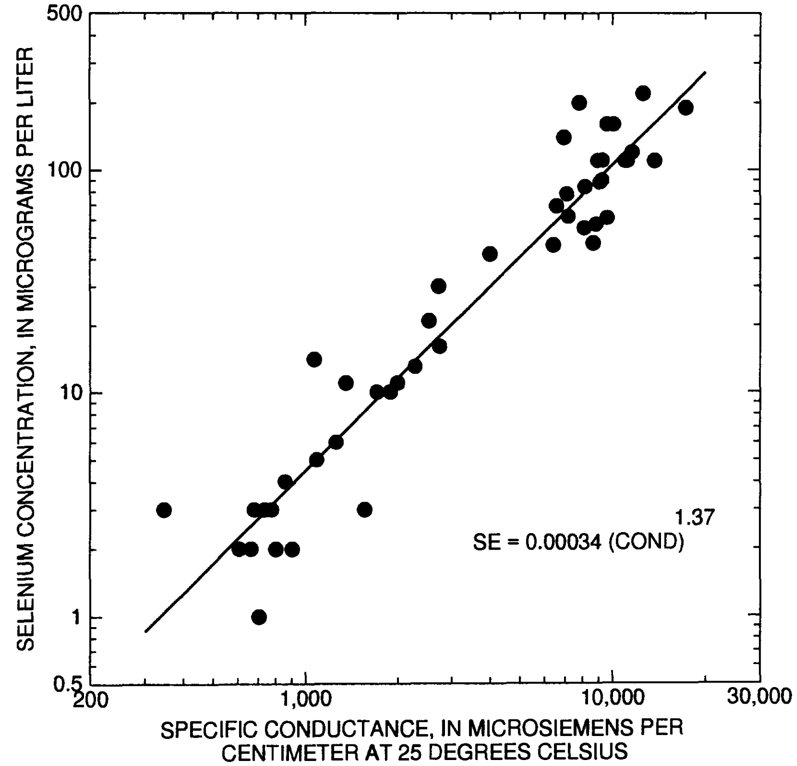


Figure 22. Relation of selenium (SE) concentrations and specific-conductance (COND) values in water samples from Lake Creek (site S-1, fig. 2), Montana.

Table 6. Annual load of dissolved solids entering Benton Lake, Montana, 1991-95

Water year	Dissolved-solids load of pumped water[1] (tons)	Dissolved-solids load of pumped water[1] Percent of total	Dissolved-solids load of natural runoff: Lake Creek[1] (tons)	Remainder of basin[2] (tons)	Combined (tons)	Percent of total	Total dissolved-solids load[3] (tons)
1991	4,398	60	1,623	1,350	2,973	40	7,371
1992	4,264	78	642	534	1,176	22	5,440
1993	2,472	16	6,900	5,737	12,637	84	15,109
1994	4,601	77	756	629	1,385	23	5,986
1995	5,909	79	874	727	1,601	21	7,510
Mean	4,329	52	2,159	1,795	3,954	48	8,283
Total	21,644	52	10,795	8,977	19,772	48	41,416

[1] Measured at Lake Creek gage (site S-1, fig. 2).
[2] Extrapolated to entire basin from volume measured at Lake Creek gage and apportioned by relative size of drainage areas.
[3] Calculated from sum of pumped water, natural runoff from Lake Creek, and natural runoff from remainder of basin.

salts formed from sulfate and chloride. The anion load in natural runoff consists almost entirely of sulfate, whereas pumped water contains approximately equal amounts of sulfate and alkalinity. In dry years when inflow primarily is pumped water, Benton Lake receives a large amount of alkalinity. In wet years, inflow to the lake contains almost no alkalinity. During 1991-95, alkalinity constituted an average of 23 percent of the total anion load.

The total selenium load to Benton Lake during 1991-95 was about 661 lb; the 5-year mean annual load was 132 lb (table 8). On average, pumped water delivered 64 lb annually, or 48 percent of the 1991-95 mean annual load. Pumped water represented 75 percent of the total water volume passing the gage. The selenium load in natural runoff was 52 percent of the 1991-95 total load, although natural flow accounted for only 25 percent of the flow of Lake Creek. Selenium loading in natural runoff was highest (86 percent) in 1993, the one wet year during the study.

Similar to dissolved solids, long-term mean annual selenium loads were estimated from data for 1970-94. The mean annual selenium load (64 lb) of pumped water during 1991-95 was slightly larger than the long-term mean annual pumped load (59 lb) because of increased pumping. More notable is that the estimated long-term mean annual selenium load from natural flow (137 lb) is larger than the mean load (69 lb) transported to Benton Lake during 1991-95. The long-term proportion of total annual selenium load contributed to Benton Lake by natural runoff is 70 percent, compared to 52 percent contributed during the study period. Although data collected during 1991-95 indicate that irrigation drainage pumped from Muddy Creek was the largest contributor of selenium to Benton Lake in some years, the long- and short-term data indicate that natural runoff from the Benton Lake basin is the major source of selenium in the basin.

Two perennial tributaries (sites S-12 and S-14) of Lake Creek that receive subsurface agricultural drainage from non-irrigated wheat fields appear to be significant sources of the dissolved solids and selenium in natural runoff in the Benton Lake basin. The estimated annual loads for these tributaries are compared to those for natural runoff in Lake Creek at the gage (site S-1, table 9). Site S-12 is the perennial tributary with the higher flow. Median discharge, dissolved-solids concentration, and selenium concentration were 0.1 ft^3/s, 12,000 mg/L, and 670 µg/L, respectively. Assuming perennial flow of 0.1 ft^3/s and that the median value of the eight concentration measurements is equal to the discharge-weighted mean concentration, 1,180 tons of dissolved solids and 131 lb of selenium flow past this site annually. For comparison, these loads are about half the dissolved-solids load but 3.5 times the selenium load from natural runoff in Lake Creek at the gage. At site S-14, median discharge, dissolved-solids concentration, and selenium concentration were 0.02 ft^3/s, 6,780 mg/L, and 2,900 µg/L, respectively. Assuming perennial flow of 0.02 ft^3/s and that the median value of the three concentration measurements is equal to the discharge-weighted mean concentration, the dissolved-solids load (135 tons) is small at site S-14 but, similar to S-12, the selenium load (114 lb) is much larger than that passing Lake Creek at the gage. The subsurface drainage system upstream from S-14 was installed in 1993. Increased selenium discharge from this site may not be apparent yet in downstream areas of the basin. These two tributaries could be the major

Table 7. Annual loads of major ions in pumped water and natural runoff entering Benton Lake, Montana, 1991-95
[Loads are in milliequivalents x 10^{10}]

Water year	Calcium	Magnesium	Sodium	Total cations	Sulfate	Alkalinity	Chloride	Total anions	Total ions
PUMPED WATER									
1991	1.69	3.56	1.74	6.99	4.23	3.51	0.20	7.94	14.93
1992	1.88	3.61	1.26	6.75	2.68	4.16	.20	7.04	13.79
1993	.88	1.92	1.07	3.87	2.15	1.57	.11	3.83	7.70
1994	1.58	3.58	1.99	7.15	3.91	3.04	.21	7.16	14.31
1995	1.66	4.35	2.87	8.88	5.97	2.65	.27	8.89	17.77
Mean	1.54	3.40	1.79	6.73	3.79	2.99	.20	6.97	13.70
Total	7.69	17.02	8.93	33.64	18.94	14.93	.99	34.86	68.50
NATURAL RUNOFF									
1991	.71	2.47	1.85	5.03	4.48	.38	.22	5.08	10.11
1992	.20	.99	.75	1.94	1.83	.01	.11	1.95	3.89
1993	3.05	10.82	8.02	21.89	21.53	.51	.84	22.88	44.77
1994	.26	1.19	.88	2.33	2.14	.009	.13	2.28	4.61
1995	.42	1.39	1.06	2.87	2.36	.24	.09	2.69	5.56
Mean	.93	3.37	2.51	6.81	6.47	.23	.28	6.98	13.79
Total	4.64	16.86	12.56	34.06	32.34	1.15	1.39	34.88	68.94
COMBINED TOTAL OF PUMPED WATER AND NATURAL RUNOFF									
1991	2.40	6.03	3.59	12.02	8.71	3.89	.42	13.02	25.04
1992	2.08	4.60	2.01	8.69	4.51	4.17	.31	8.99	17.68
1993	3.93	12.74	9.09	25.76	23.68	2.08	.95	26.71	52.47
1994	1.84	4.77	2.87	9.48	6.05	3.05	.34	9.44	18.92
1995	2.08	5.74	3.93	11.75	8.33	2.89	.36	11.58	23.33
Mean	2.47	6.78	4.30	13.54	10.26	3.22	.48	13.95	27.49
Total	12.33	33.88	21.49	67.70	51.28	16.08	2.38	69.74	137.44

Table 8. Annual load of selenium entering Benton Lake, Montana, 1991-95

Water year	Selenium load of pumped water[1]		Selenium load of natural runoff				Total selenium load[3] (pounds)
	Pounds	Percent of total	Lake Creek[1] (pounds)	Remainder of basin[2] (pounds)	Combined (pounds)	Percent of total	
1991	64.2	57	26.5	22.0	48.5	43	112.7
1992	57.7	71	12.6	10.5	23.1	29	80.8
1993	34.9	14	115.5	96.0	211.5	86	246.4
1994	68.0	70	16.2	13.5	29.7	30	97.7
1995	93.6	76	16.4	13.6	30.0	24	123.6
Mean	63.7	48	37.4	31.1	68.6	52	132.2
Total	318.4	48	187.2	155.6	342.8	52	661.2

[1] Measured at Lake Creek gage (site S-1, fig. 2).
[2] Extrapolated to entire basin from volume measured at Lake Creek gage and apportioned by relative size of drainage areas.
[3] Calculated from sum of pumped water, natural runoff from Lake Creek, and natural runoff from remainder of basin.

Table 9. Annual loads of dissolved solids and selenium in natural runoff in Lake Creek and perennial tributaries

Site number (fig. 2)	Annual load in natural runoff	
	Dissolved solids (tons)	Selenium (pounds)
S-1[1]	2,159	37
S-12[2]	1,180	131
S-14[2]	135	114

[1] Data for 1991-95 from tables 6 and 8.

[2] Data computed from an assumed constant flow of water equal to the median discharge and concentration of periodic water samples listed in table 17.

sources of selenium in Lake Creek. As noted in the preceding "Lake Creek Water Quality" section, the importance of streamflow at site S-12 as a source was indicated by the water-quality data shown in figure 15.

Water Quality

The water quality of Benton Lake is variable, depending on factors such as the relative amount of pumped water or natural runoff that recently entered the lake, the amount of evapoconcentration that has occurred, and whether a pool is operated as a flow-through unit or is flooded seasonally. Dissolved-solids concentrations in water samples from Benton Lake ranged from 516 to 7,740 mg/L (table 17), with a median of 2,090 mg/L. Concentrations were highest during the spring (pre-pumping) and mid-summer. Concentrations commonly decreased when relatively dilute water was pumped into the refuge from Muddy Creek. Concentrations in Pools 1 and 2 tended to be lower and remained more constant than in other pools owing to the effect of inflows from Lake Creek and their operation as flow-through units. In contrast, Pools 3-6, which are seasonally flooded and are not flushed by flow-through water management, have generally higher and more variable concentrations of dissolved solids. The water type in Benton Lake generally is magnesium-sodium sulfate. When large amounts of pumped water have been added, bicarbonate becomes a dominant ion with sulfate.

The general characteristics and trends in water quality in Benton Lake can be more fully assessed from specific-conductance data because numerous specific-conductance data are available. Since 1991, USFWS personnel systematically measured specific conductance in each pool of Benton Lake. Dissolved-solids concentrations can be calculated from specific-conductance values using the regression equation in figure 23 developed from lake-water samples collected during this study (table 17).

In 1991-95, the specific conductance of water near the outlets of Pools 1 and 2 ranged from 465 to 4,570 µS/cm (according to data collected by the staff of the Benton Lake NWR). The trends in specific-conductance values over time were similar in both pools. Data for Pool 1 for 1991-95 are shown in figure 24. Whenever pumped water was added to Pool 1, specific-conductance values decreased to less than 900 to 1,200 µS/cm. The values were lowest during snowmelt runoff in early spring 1993. Specific-conductance values increased after cessation of pumping but were higher than 3,000 µS/cm only briefly in late spring 1994 and summer 1995.

In 1991-95, the specific conductance of water in Pools 3-6 varied seasonally, depending on the interplay of filling and evaporation. Specific-conductance values tended to be low when pools were full and much higher when pools had little water. Specific-conductance values in Pools 3-6 increased during the spring, summer, and fall in response to evapoconcentration. Values as high as 7,000-10,000 µS/cm resulted occasionally when most water had evaporated. When water was added to a pool, the specific conductance generally decreased significantly because the inflow water had a moderate to low specific-conductance, generally ranging from about 500-2,500 µS/cm depending on the source of the water. Although seasonal differences in dissolved-solids concentrations related to water volume were substantial, the long-term data show no significant increase in seasonal maximum concentrations over time. This evidence would indicate that salts are being removed effectively at a rate nearly equivalent to that of the annual or several-year inflow.

Specific-conductance data measured at the southeastern corner of Pool 3 (fig. 24) are representative of the seasonal fluctuations in specific conductance that occurred in Pools 3-6 in 1991-95. In Pool 3, specific-conductance values ranged from 673 to 6,300 µS/cm. Pumped water was added to Pool 3 from the Interunit Canal twice each year in 1991 and 1992 and once each year in 1993 and 1994, and three times in 1995. With one exception, each addition of water significantly lowered the specific conductance of the lake water. In May 1995, a small amount of added water does not

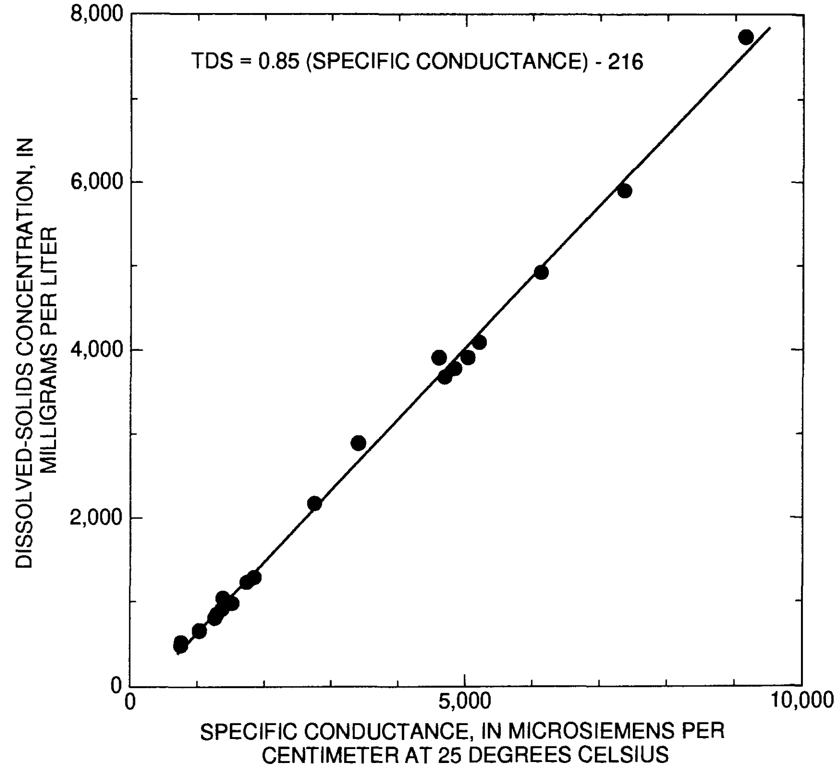


Figure 23. Relation of dissolved-solids (TDS) concentrations and specific-conductance values in water samples from Benton Lake, west-central Montana.

appear to have lowered specific conductance in Pool 3. The specific conductance at the beginning and end of this 52-month period was virtually the same even though dissolved solids had been added each year.

Selenium concentrations in Benton Lake ranged from <1 to 4 µg/L (table 17), with a median of <1 µg/L. These concentrations are much lower than those in the natural runoff from the Benton Lake basin and are even lower than the median selenium concentration (3 µg/L) in the relatively dilute water pumped from Muddy Creek. Assuming that evaporative processes are occurring in this closed basin, the decrease in selenium concentrations in Benton Lake relative to the concentrations in inflows indicates that selenium is being removed from the water. The removal of selenium from water and its subsequent accumulation in bottom sediment of wetlands is common (Lemly and Smith, 1987). In Benton Lake, removal of dissolved selenium is rapid such that almost all selenium transfer occurs in Pools 1 and 2 (Nimick and others, 1996; Zhang and Moore, 1996, 1997b,d). The most important removal mechanism probably is chemical reduction and conversion of dissolved selenium to organic or elemental selenium by bacteria in surficial sediment (Oremland and others, 1989, 1990, 1991). Selenium also can be removed from water and concentrated in surficial sediment through ingestion by aquatic organisms or adsorption to suspended sediment and subsequent settling of the dead organisms and sediment (Lemly and Smith, 1987; Weres and others, 1989, 1990).

On the basis of stable-isotope data (tables 17 and 18), most surface water is affected by evaporation (fig. 11) in the Benton Lake basin. Samples affected by evaporation plot closer to the upper right part of the graph and, in comparison to unevaporated samples, are enriched in oxygen-18 relative to deuterium. Most of the stable-isotope samples from Benton Lake were collected in 1992 and the delta deuterium and delta oxygen-18 values for these samples define an evaporation line. If extended, this line intersects the points representing pumped water in Lake Creek, indicating that the pumped water was the primary source of the evaporated water in Benton Lake in 1991. Gaging records also indicate that much of the inflow to Benton Lake in 1991 was from pumped water.

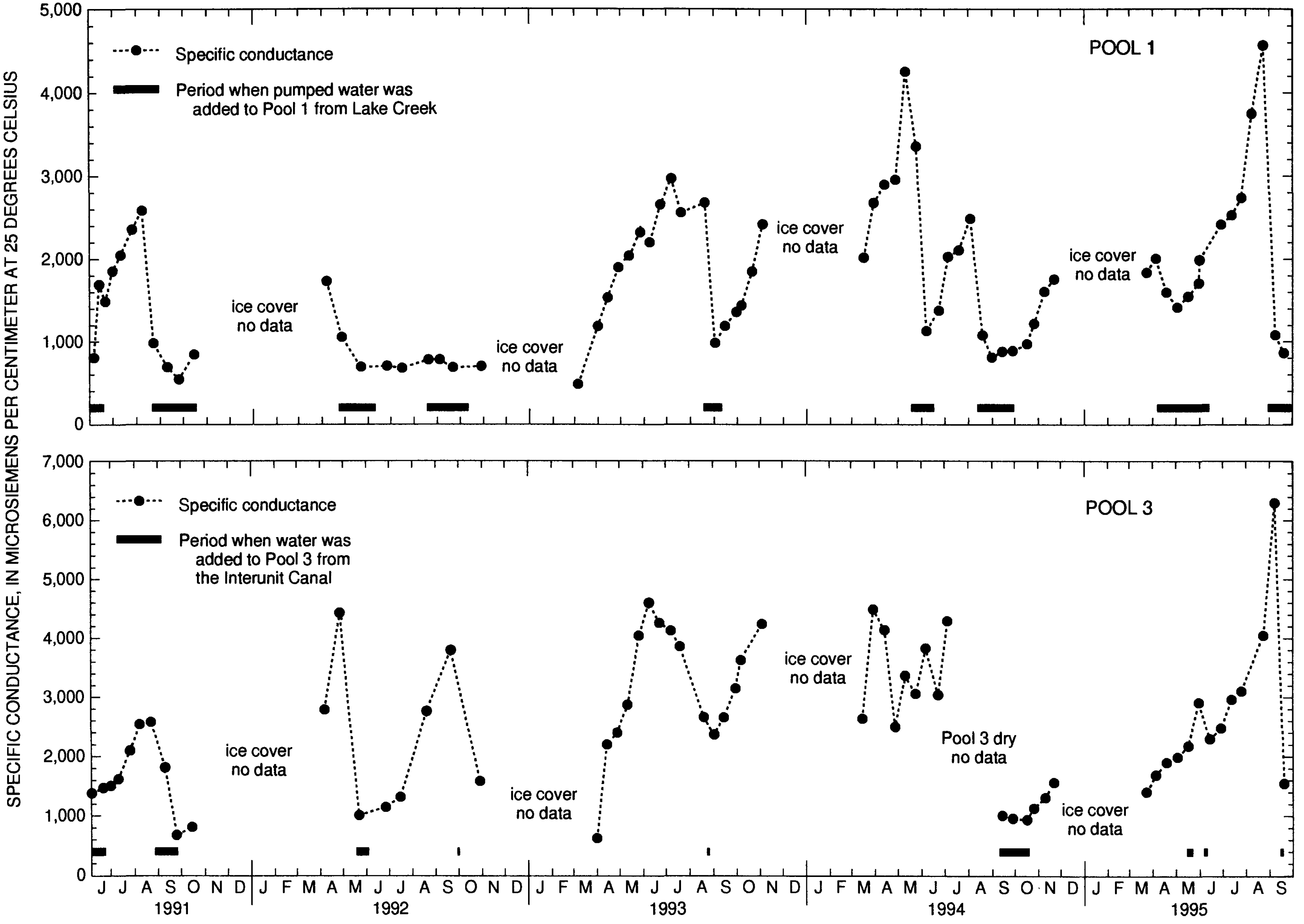


Figure 24. Specific-conductance record for Benton Lake Pools 1 and 3, west-central Montana, 1991-95. Data provided by staff at Benton Lake National Wildlife Refuge (Erich Gilbert, written commun., 1994; Mindy L. Meade, written commun., 1995). The location of the Interunit Canal is shown in figure 26.

FATE OF DISSOLVED SOLIDS IN BENTON LAKE

Because Benton Lake has no outlet, solutes delivered to the lake potentially could accumulate. If dissolved solids were not being removed or chemically sequestered from the lake water, the increase in dissolved-solids concentrations over time in Benton Lake would be dramatic. Pools 1 and 2 are operated as flow-through units and, because of the flushing action, no long-term buildup of dissolved solids is expected. The most likely areas for solutes to accumulate would be in Pools 3-6, which have no outlet. Results of this study indicate that dissolved solids are not accumulating in Pools 3-6. As discussed in this section, this conclusion was reached after developing and testing several hypotheses concerning possible salt-removal mechanisms.

Dissolved-Solids Accumulation in Benton Lake

Assuming that the volume of water required to fill Benton Lake has not changed significantly since dikes were constructed in 1961 and that no removal mechanisms were active, dissolved-solids concentrations would be expected to rise with each year's addition of solutes. Assuming the mean annual discharge-weighted dissolved-solids concentrations for pumped water (646 mg/L) and natural runoff (1,780 mg/L) computed for 1991-95 (table 4) apply for the 1961-95 period, concentrations in the lake in 1995 should be approximately 34 times greater than these concentrations, or between 22,000 and 60,500 mg/L, if the lake were full of water. Equivalent specific-conductance values would be 26,100 and 71,400 μS/cm based on the equation shown in figure 23. Specific-conductance values in this range have not been measured in Benton Lake.

The 1974-95 record of specific-conductance measurements made by the USFWS provide a long-term history of water quality in Benton Lake. The median and range of specific-conductance values for each year for each pool in Benton Lake are shown in figure 25. These data may not provide a complete representation of water quality in the lake because the quality of the pre-1990 data is unknown and because data collection before 1990 does not appear to have followed a systematic plan. For example, only one value exists for some pools in some years whereas as many as nine values exist for some pools in other years. Despite the uncertainties, the older data are useful.

Morrison-Maierle, Inc. (1984) examined the specific-conductance data for Benton Lake for 1975-81. The data used were the same as the 1975-81 data shown in figure 25. Morrison-Maierle, Inc. (1984) noted that specific-conductance values appeared to be increasing in 1975-81 and assumed that specific-conductance values would continue to increase after 1981. They projected the trend of increasing values into the future and concluded that specific-conductance values would reach a hazard level of 16,000 μS/cm in 16 to 50 years (Morrison-Maierle, Inc., 1984). On the basis of data for the longer 1974-95 period, no trend of increasing specific-conductance values is apparent and increases to the 16,000 μS/cm level are unlikely in the projected timeframe.

The long-term record shows that specific-conductance values vary from year to year and that patterns of increasing or decreasing specific conductance are persistent over several consecutive years. No significant trend of increasing specific conductance over time is apparent, however, in the longer-term 1974-95 record. If salinity levels are increasing in Pools 3-6, the rate of increase is small enough to be masked by seasonal or multiyear variability. Some of the variability has possible explanations. In 4 years (1975, 1978, 1979, and 1989), natural runoff was exceptionally large, exceeding 9,000 acre-ft in each year (table 5). The lowest specific-conductance values in Pools 3-6 occurred in these years, probably because the large runoff volumes had relatively low dissolved-solids concentrations and relatively little evapoconcentration occurred. Specific-conductance values can be relatively high in units that are dry for much of the summer. This condition occurred in Pool 5 in 1990 and in Pool 3 in 1993 and 1994. When specific-conductance values are high, the volume and surface area of water in a pool are very small.

If salts were accumulating in Pools 3-6, the soluble portion of these salts presumably would redissolve or reappear in lake water after a pool is flooded. To determine if solutes reappear in flooded pools, the distribution of specific-conductance values was mapped in Pool 5 on September 25, 1992 (fig. 26), and in Pool 3 on September 1, 1993 (fig. 27), shortly after each pool had been partially filled. The maps were used to determine the increase in the specific conductance of added water. Initially, each pool was virtually empty except for a small amount of residual water with high specific conductance. Water was added to each pool from the east end of the Interunit Canal. During filling, pre-existing water was either mixed with inflow water or pushed to the opposite ends of the pool.

Pool 5 was filled September 4-17, 1992, with water pumped from Muddy Creek. The specific conductance of the added water ranged from 780 to

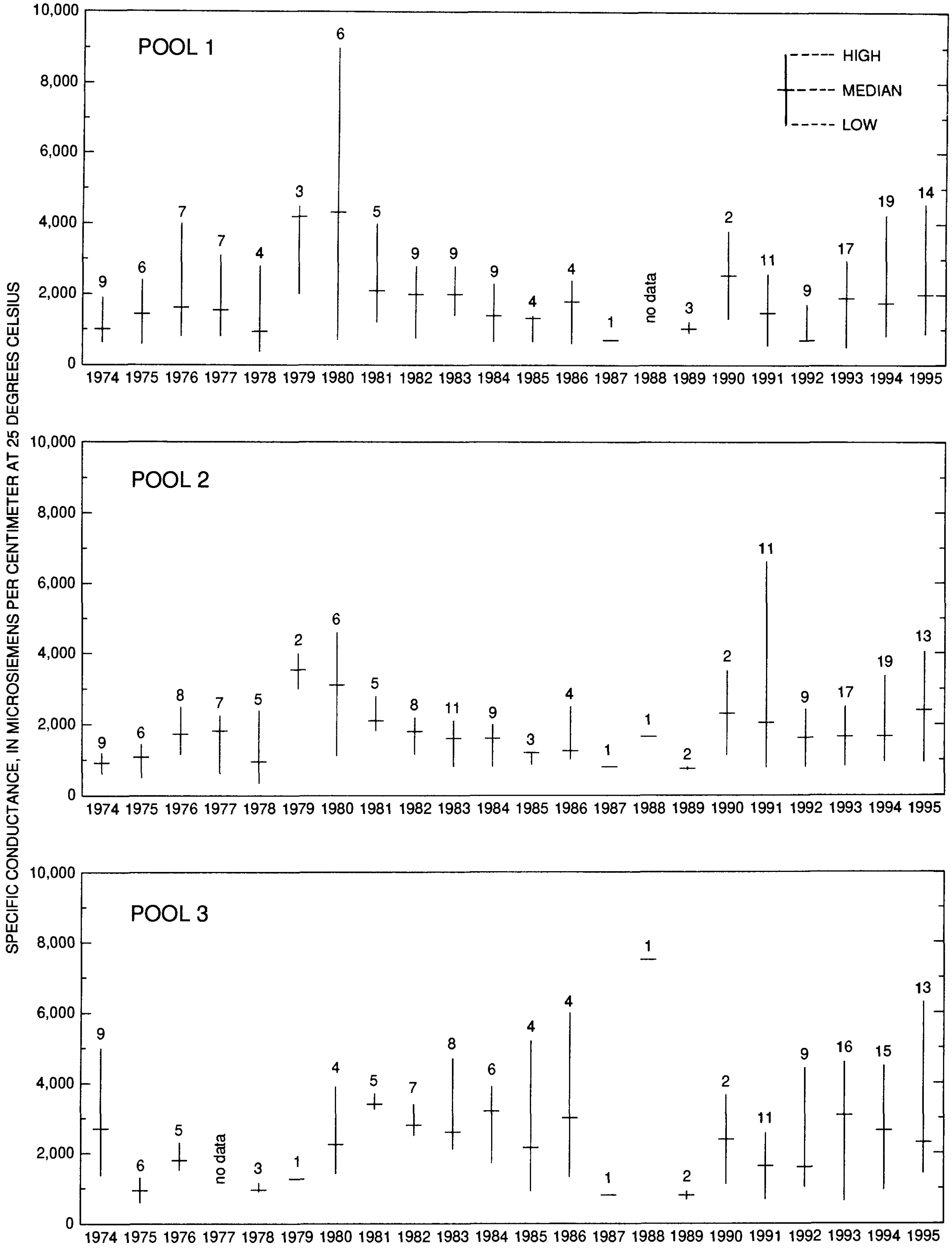


Figure 25. Annual low, median, and high specific-conductance values for Benton Lake Pools 1-6, west-central Montana, 1974-95. The number of measurements is indicated for each year. Data provided by staff at Benton Lake National Wildlife Refuge (Stephen J. Martin, written commun.,1992; Erich Gilbert, written commun., 1994; Mindy L. Meade, written commun., 1995).

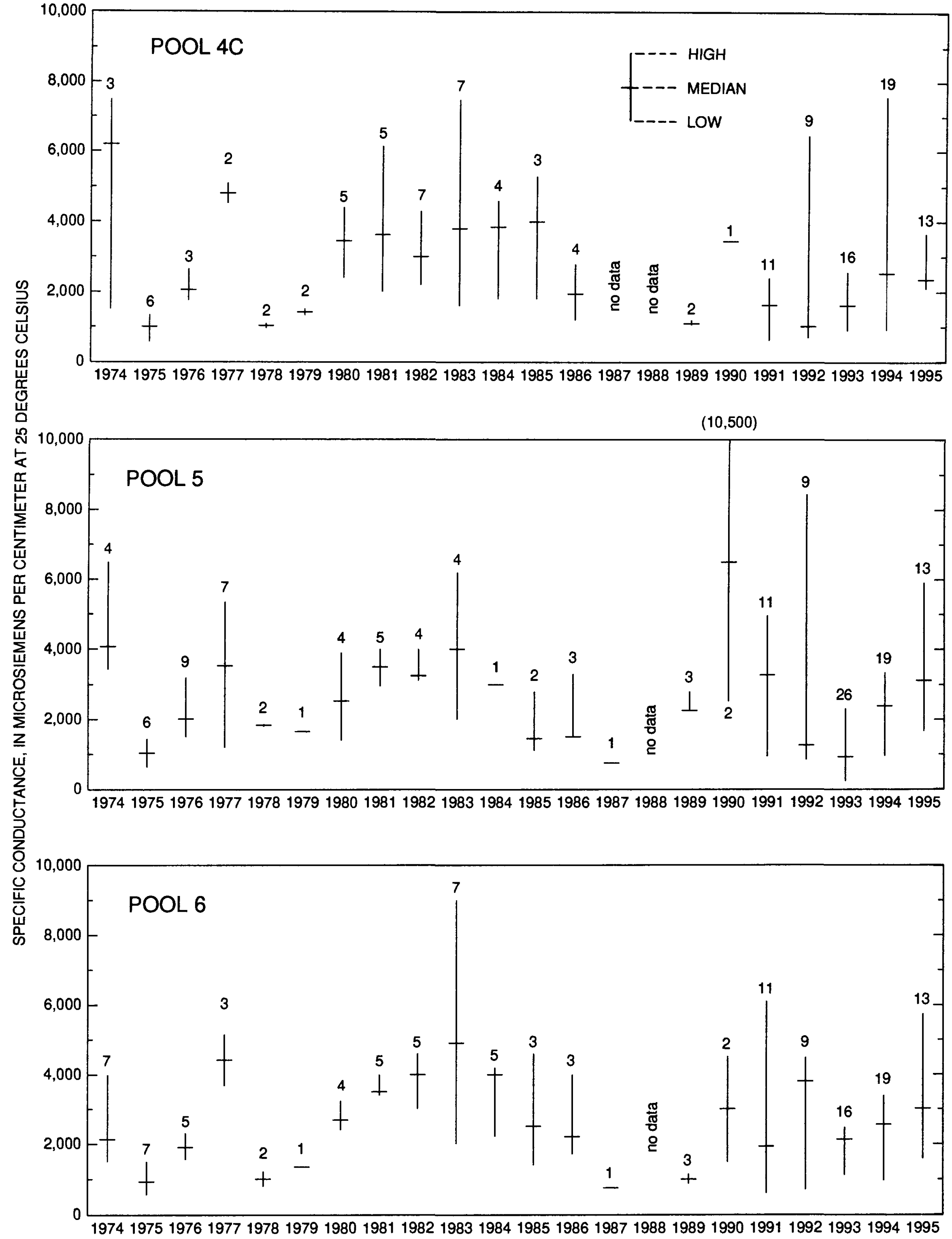


Figure 25. Annual low, median, and high specific-conductance values for Benton Lake Pools 1-6, west-central Montana, 1974-95. The number of measurements is indicated for each year. Data provided by staff at Benton Lake National Wildlife Refuge (Stephen J. Martin, written commun.,1992; Erich Gilbert, written commun., 1994; Mindy L. Meade, written commun., 1995). (Continued)

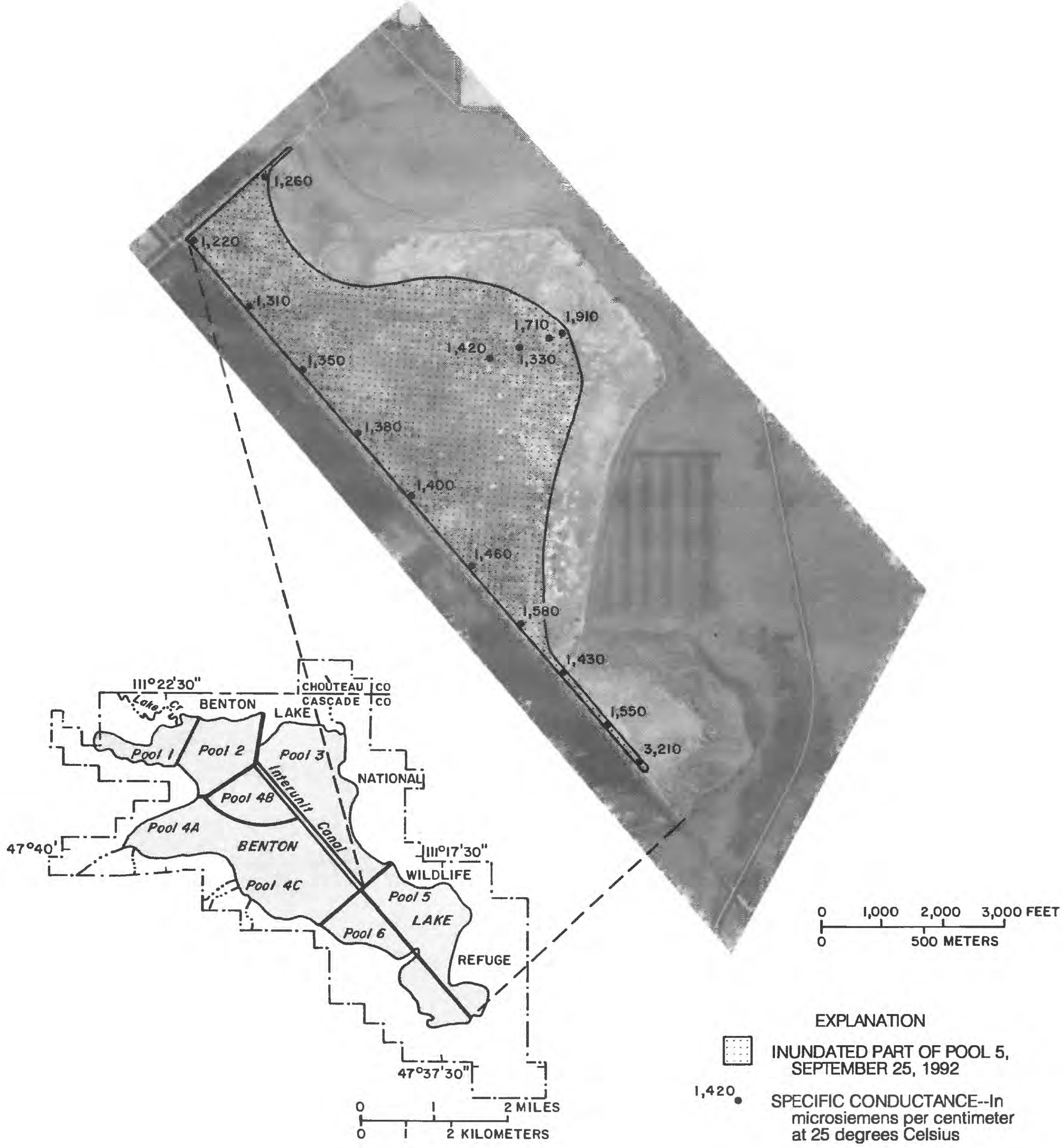


Figure 26. Specific conductance of lake water on September 25, 1992, in Benton Lake Pool 5, west-central Montana.

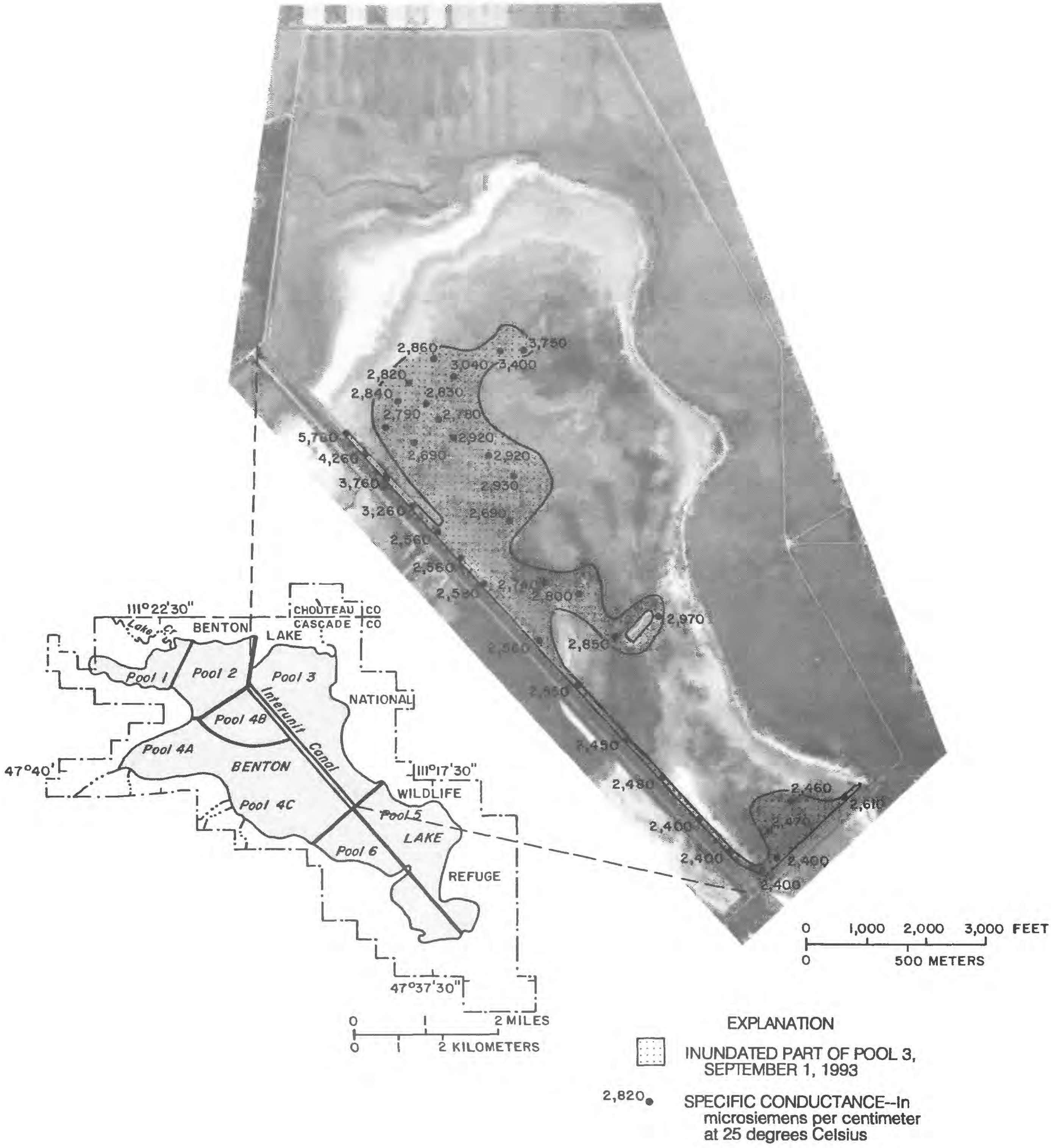


Figure 27. Specific conductance of lake water on September 1, 1993, in Benton Lake Pool 3, west-central Montana.

890 µS/cm. The lakebed had been dry since May 1992. Approximately 711 acre-ft of water were added and covered 670 surface acres of Pool 5. The final water depth was as much as 1.2 ft in the pool, except in the borrow ditches parallel to the dikes, where water depth was about 4 ft. The added water had a discharge-weighted mean dissolved-solids concentration of 523 mg/L. After filling, specific-conductance values in most of the pool were between 1,220 and 1,580 µS/cm (fig. 26) or about 50-100 percent higher than values of the inflow water. Higher values (as much as 3,210 µS/cm) occurred at the ends of the pool farthest from the inflow point. These higher values probably resulted from preexisting water that was pushed by inflowing water and from the initial dissolution of salts as the water was pushed over the dry lakebed. The general increase in specific conductance observed throughout the pool may have resulted from dissolution of salt crusts that had formed on the lakebed during the previous hot summer days.

Another monitored refill occurred in 1993 in Pool 3. About 233 acre-ft of water was added on August 23-27, 1993. Most of the inflow had specific-conductance values of 2,280-2,430 µS/cm. The added water had a discharge-weighted mean dissolved-solids concentration of 1,770 mg/L. In the main part of the pool, final specific-conductance values on September 1, 1993, were between 2,400 and 2,970 µS/cm (fig. 27), or less than about 25 percent higher than the inflow water. Higher values (as much as 5,780 µS/cm) were measured at the far ends of the pool. Although the pool had been empty much of the summer, the unseasonably cool, wet weather during summer 1993 did not promote formation of salt crusts on the lakebed. Therefore, the post-filling specific-conductance values did not increase substantially.

Another example of changes in the specific conductance of lake water when a pool is filled is illustrated by the spring 1993 filling of Pool 5. The large volume of snowmelt runoff in March 1993 provided water with low specific-conductance values (about 346-1,100 µS/cm) to Benton Lake. Pool 5 was filled with this water, and specific-conductance values in March and April in Pool 5 ranged from 502 to 995 µS/cm (Erich Gilbert, written commun., 1994). These data emphasize the point that although Pool 5 has been operated as a closed-basin pool since 1961, low specific-conductance values similar to recently supplied water still occur in the pool.

Salt Removal Mechanisms

Removal of salts from closed-basin lakes has long been recognized as a common natural phenomenon (Langbein, 1961). During the early years of study of closed-basin lakes, scientists assumed that all salts delivered to a lake remained in the lake and attempted to calculate the age of closed-basin lakes by dividing the amount of salt contained in the lake's water by the annual average inflow of salts to the lake. Later work showed that this reasoning was flawed and that the amount of salt in many closed-basin lakes is much less than the total amount of salt delivered to the lake over the period of existence of the lake. This realization led to studies that more closely examined the salt balance of closed-basin lakes. The primary components of the salt balance are inflow events, which freshen the water while delivering additional salt; evaporation, which concentrates salt in the remaining lake water and leads to precipitation of evaporite minerals; and removal mechanisms, which cause salts to be lost from the lake or isolated in the lakebed. Site-specific physical, chemical, and hydrologic conditions affect the salt balance for each lake and can explain the large range in salinity levels (less than 1 percent to more than 25 percent by weight of salts) of the many closed-basin lakes in the Western United States (Langbein, 1961). Several important removal mechanisms have been proposed in the literature, including burial or entrapment of salts in lakebed sediment, removal of dry lakebed material by wind, advection of salts through subsurface basin leakage, and diffusion of concentrated lake water into the pore water in lakebed sediment (summarized in Langbein, 1961; Last, 1984; Sanford and Wood, 1991; and Rogers and Dreiss, 1995).

Benton Lake presumably has existed as a closed-basin lake since its formation by deposition of glacial till during late Pleistocene time and has had ample time to become saline, as has occurred in other closed-basin lakes, or playas, in the northern Great Plains (Last, 1984). Presumably, dissolved solids have been delivered to Benton Lake since deglaciation some 10,000 or more years ago. With the development of dryland agriculture over the past 50-80 years and the accompanying increase of saline seeps, the dissolved-solids load delivered to Benton Lake probably has increased. Since 1961, pumping of water from Muddy Creek has contributed additional dissolved solids to the lake.

Dissolved solids introduced into Pools 3-6 at Benton Lake appear to be removed or become isolated from the lake-water system. The mechanisms causing removal or isolation of the dissolved solids at Benton Lake have not been studied previously. If these mechanisms were known, management of the refuge potentially could be improved. To study this question, a hypothesis about salt removal and isolation was developed and then tested with laboratory and field experiments.

The hypothesis developed concerning salt removal and isolation has several components. First, the salts that precipitate in lakebed sediment as lake water evaporates are primarily sulfates and carbonates. These salts form in the surficial lakebed sediment. Second, some of these salts are removed by wind erosion when a lakebed is dry, a mechanism noted at other playa lakes (Last, 1984; Wood and Sanford, 1995). Third, when a pool is reflooded, sulfate salts dissolve readily while only a small amount of the carbonates dissolve because the lake water quickly becomes saturated with respect to the carbonates. Therefore, carbonates become sequestered in the lakebed sediments but sulfates do not. Fourth, other processes such as diffusion, advection, and various ion-removal mechanisms also may be important. Various experiments and data-collection efforts were conducted to study this multi-component hypothesis.

Precipitation of Salts

The specific minerals that precipitate during evaporation of lake water depend on the composition of the initial water (Eugster and Jones, 1979). The solute-loading calculations demonstrated that the major components in pumped water are primarily magnesium, sodium, calcium, sulfate, and alkalinity. Sodium-magnesium sulfate and magnesium-calcium carbonate minerals would be the primary precipitates produced from pumped water. The major ions in natural runoff are primarily magnesium, sodium, and sulfate. On the basis of these water compositions, sodium-magnesium sulfate minerals would be the primary precipitates produced from this water.

An evaporation experiment was conducted to determine what minerals precipitate from lake water. Twenty-four liters of water collected from Benton Lake Pool 3 on June 1, 1993, were cumulatively evaporated in a 4-L beaker placed in a drying oven at 35 °C for 7 weeks. Periodically, water was added to keep the beaker filled to within 5 cm of its top. When evaporation was complete, salts were collected from the sides of the 4-L beaker. One sample (Salt 1) was collected from the top of the evaporation beaker, where the first salts formed during evaporation and were expected to be primarily carbonates. The second sample (Salt 2) was collected from the middle of the evaporation beaker, where salts formed later in the experiment and were expected to be primarily sulfates and chlorides. The minerals in the salt samples were identified by X-ray diffraction (XRD) (John M. Neil, U.S. Geological Survey, written commun., 1994) (table 10).

Thenardite, konyaite, and bloedite were the sodium-magnesium sulfate minerals identified in the samples of Salt 1 and 2. These minerals are part of a suite of highly soluble hydrated sodium-magnesium sulfate minerals commonly associated with saline seeps (Skarie and others, 1987; Keller and others, 1986a,b; Timpson and others, 1986) and weathered marine shale (Whittig and others, 1982; Evangelou and others, 1984; Presser and others, 1990). Other sodium-magnesium sulfate minerals in this suite also may have precipitated because hydrated sodium-magnesium sulfate minerals are unstable and readily convert to more-hydrated or less-hydrated forms in response to temperature and moisture conditions. For example, Whittig and others (1982) reported that mirabilite ($Na_2SO_4 \cdot 10H_2O$) and epsomite ($MgSO_4 \cdot 7H_2O$) converted to thenardite (Na_2SO_4) and bloedite [$Na_2Mg(SO_4)_2 \cdot 4H_2O$] during XRD analysis because of desiccation. For the purpose of this study, knowing exactly which minerals in the suite of hydrated sodium-magnesium sulfates are present is not essential because all these minerals are highly soluble and would redissolve from the lakebed if a pool were reflooded.

Magnesium-calcium carbonate minerals also were identified by XRD in samples of Salt 1 and 2 but in smaller quantities than sulfate minerals. The carbonate minerals included calcite, monohydrocalcite, and nesquehonite (table 10).

After the initial XRD analysis, the two salt samples were washed with deionized water to remove the soluble sodium-magnesium sulfate minerals in hopes of eliminating any non-carbonate sources producing responses within the XRD spectra that would interfere with identification of the carbonates. XRD of the washed samples indicated that additional carbonate minerals (table 10) were present; however, these additional minerals could have been formed during washing. Monohydrocalcite is a metastable carbonate mineral that forms in magnesium-rich water (Hull and Turnbull, 1973) and sulfate-rich water (John M. Neil, oral commun., 1994).

Two sediment samples collected from Benton Lake also were examined by XRD to see if the minerals precipitated in the laboratory experiment were the same as minerals found in the field. The field samples were a surficial salt-crust sample collected from Pool 3 on August 18, 1993, and a lakebed sample collected from Pool 5 on June 12, 1992. These samples contained calcite and monohydrocalcite but no sodium-magnesium sulfate minerals (table 10). The lack of sodium-magnesium sulfate minerals in one salt-crust sample probably can be attributed to the wet conditions in summer 1993 that did not promote sufficient evaporation from the lakebed to precipitate these highly sol-

Table 10. Relative abundance of minerals identified by X-ray diffraction in samples of lakebed sediment, a salt crust, and in salts precipitated from evaporated lake water

[Abbreviations: M, major; m, minor; p, possibly present; tr, trace. Symbol: --, not present]

Mineral	Relative mineral abundance					
	Salt 1[1]	Salt 1, washed[2]	Salt 2[3]	Salt 2, washed[4]	Salt crust, Benton Lake Pool 3[5]	Lakebed sediment, Benton Lake Pool 5[6]
		Sodium-magnesium sulfate minerals				
Thenardite [Na_2SO_4]	M	--	m	--	--	--
Konyaite [$Na_2Mg(SO_4)_2 \cdot 5H_2O$]	M	--	--	--	--	--
Bloedite [$Na_2Mg(SO_4)_2 \cdot 4H_2O$]	M	--	M	--	--	--
		Magnesium-calcium carbonate minerals				
Hydromagnesite [$MgCO_3 \cdot H_2O$]	--	M[7]	--	m	--	--
Nesquehonite [$MgCO_3 \cdot 3H_2O$]	M	m	p	--	--	--
Dypingite [$Mg_5(CO_3)_4(OH)_2 \cdot 5H_2O$]	--	M[7]	--	M	--	--
Calcite [$CaCO_3$]	m	--	--	--	tr	p
Monohydrocalcite [$CaCO_3 \cdot H_2O$]	m	M	--	M	m	tr
Huntite [$Mg_3Ca(CO_3)_4$]	--	p	--	--	--	--
		Silicate minerals				
Quartz	--	--	--	--	M	M
Albite	--	--	--	--	--	tr
Muscovite	--	--	--	--	tr	m
Illite	--	--	--	--	tr	tr
Kaolinite	--	--	--	--	tr	tr
Chlorite	--	--	--	--	--	tr

[1] Salt precipitated from water collected from Benton Lake Pool 3 on June 1, 1993, and evaporated to dryness. Salt was white and collected from top of evaporation beaker.

[2] Salt precipitated from water collected from Benton Lake Pool 3 on June 1, 1993, and evaporated to dryness. Salt was white and collected from top of evaporation beaker. Salts washed with deionized water to remove soluble sulfate salts.

[3] Salt precipitated from water collected form Benton Lake Pool 3 on June 1, 1993, and evaporated to dryness. Salt was brown and collected from middle of evaporation beaker.

[4] Salts precipitated from water collected from Benton Lake Pool 3 on June 1, 1993, and evaporated to dryness. Salt was brown and collected from middle of evaporation beaker. Salt was washed with deionized water to remove soluble sulfate salts.

[5] Surface samples collected from dry lakebed at site H, August 18, 1993.

[6] 0-3 in.-sample collected from site I, June 12, 1992.

[7] Probably converted from nesquehonite when sample was washed.

uble minerals from the interstitial water in the sediment.

One environmental factor that affects mineral precipitation is temperature. The solubilities of sodium-magnesium sulfate minerals decrease as temperature decreases (Last, 1984; Arndt and Richardson, 1989). Furthermore, as interstitial water in lakebed sediment freezes, the remaining solution becomes more concentrated and even very soluble minerals are likely to precipitate (Arndt and Richardson, 1985; Timpson and others, 1986). These two processes can enhance mineral precipitation in winter and form salt crusts susceptible to wind erosion.

In summary, the results of the evaporation experiment demonstrate that sodium-magnesium sulfate minerals are the primary precipitates from lake water. The experiment, as well as examination of surficial lake-bed sediment, demonstrated that carbonate minerals also precipitate.

Wind Erosion of Salts

If salts are removed by wind from dry lakebeds, the salt content of the lakebeds should be less than expected. The mean annual dissolved-solids input to Benton Lake from Lake Creek in 1991-95 was 8,283 tons (table 6). Dissolved solids are expected to pass through Pools 1 and 2 and accumulate in Pools 3-6, which are closed basins. Assuming a normal full-capacity surface area of 4,000 acres for Pools 3-6, then 0.095 pound of salt per square foot of lakebed (lb/ft^2) should accumulate annually. In the 31 years between dike construction at Benton Lake and 1992, the total accumulation of soluble salt should have been 2.95

lb/ft^2. As determined by measurements in 1992, soluble salt content of the upper 3 in. of lakebed sediment ranges from 0.040 to 0.51 lb/ft^2. Clearly, soluble salts are being removed from surficial sediments in Benton Lake. This conclusion is supported by the lack of an increasing trend in dissolved-solids concentration over time.

The question of whether salts are removed from dry lakebeds by wind erosion was addressed indirectly by conducting periodic soluble-salt inventories of lakebed sediments. Net gain or loss of soluble salts in lakebed samples was compared with the water management of the pool between sample-collection dates.

Surficial samples (upper 3 in.) of lakebed sediment were collected periodically in 1992 from sites in Pools 3 and 5 (fig. 28). All samples consisted of gray, dense, inorganic silty clay. The soluble-salt content of the sediment was quantified using a 5:1 water extract (Rhoades, 1982). A similar extraction method was used by Whittig and others (1982), See and others (1992), and Zawislanski and others (1992) to determine concentrations of soluble constituents in shale, soil, and lakebed sediment, respectively. Samples were oven-dried at 75 °C and ground to a powder in a mechanical grinder. Extracts were prepared by mixing 100 g deionized water and 20 g sediment in a centrifuge tube. The tubes were shaken on a mechanical shaker for 1 hour and centrifuged at 2,500 revolutions per minute for 10 minutes. The specific conductance of the supernatant liquid was measured after filtration through a 0.45-µm filter. Triplicate analyses of individual samples demonstrated that the precision (<5 relative percent difference) of the laboratory method was excellent. Analysis of replicate field samples collected within 1-2 ft of each other showed that onsite variability was high. The relative percent difference was <50 percent in eight triplicate sets of field samples but <30 percent in six of these eight sets. In addition, some extracts were analyzed for major ions and selenium. Specific-conductance values for sediment extracts were converted to dissolved-solids concentrations using a linear-regression equation developed from the analytical data for the samples analyzed in the laboratory (fig. 29). Lakebed sediment was assumed to have a density of 1.5 g/cm^3.

Inflow to a pool was monitored periodically by Benton Lake NWR staff (Erich Gilbert, written commun., 1993). Daily discharge was determined from the mean of the 1-3 discharge measurements made each day at the inflow structure. Total inflow for a filling event was calculated as the sum of the daily values. Specific conductance was measured 1-3 times per day, and these values were averaged to obtain the daily mean specific conductance. Daily mean specific conductance was converted to a dissolved-solids concentration using a regression equation. Water with specific-conductance values less than 1,200 µS/cm was pumped from Muddy Creek, and the regression equation for pumped water (fig. 21) was used. Water with specific-conductance values greater than 1,200 µS/cm was a mixture of pumped water and natural runoff, and the equation developed for lake-water samples (fig. 23) was used. Daily dissolved-solids loads were calculated from the daily mean discharge and daily mean dissolved-solids concentration.

Sediment samples were collected from Pool 3 in 1992 to determine what happens to lakebed salts when a pool is filled during the summer and the lakebed is kept inundated for several months. Presumably, no salt would have been lost to wind erosion after filling because the lakebed was wet during the summer. The first lakebed sediment samples were collected on April 22, 1992, when the lakebed was muddy but no standing water was present. The pool was flooded with 766 acre-ft of water between May 18 and June 4, 1992. The added water had an average specific conductance of 814 µS/cm, or a dissolved-solids concentration of 507 mg/L based on the regression equation for pumped water in figure 21. The added water flooded 580 acres of Pool 3. Assuming the water was spread evenly over this area and evaporated, the increase in salt content of the lakebed would have been 0.042 lb/ft^2 of lakebed. The pool had been dry for several weeks when the lakebed was sampled again on September 3 or 25, 1992. The concentrations of soluble salt in upper 3-in. lakebed samples generally increased during the summer (table 11). The median increase in 10 samples was 465 mg/L, or an increase in salt content of 0.054 lb/ft^2 of lakebed. This median increase is similar to the expected value that was calculated, indicating that the dissolved solids of the added water probably became stored in the surficial lakebed sediment.

Sediment samples were collected from Pool 5 in 1992 to determine what happens to lakebed salts when a pool is dry for most of the summer and no water (except precipitation) is added. The first lakebed sediment samples were collected on June 12, 1992, when the lakebed was muddy but no standing water was present. The lakebed dried soon after this sampling and remained dry except during brief wetting caused by rain through the second sampling on September 3, 1992. The concentrations of soluble salt in the 5:1 water extracts of the upper 3-in. lakebed samples generally decreased during the summer (table 12). The median decrease in 13 samples over the 3-month period was 810 mg/L. This loss of soluble salt is attributed to wind erosion of the salts that form on the lakebed surface, although no direct evidence supporting

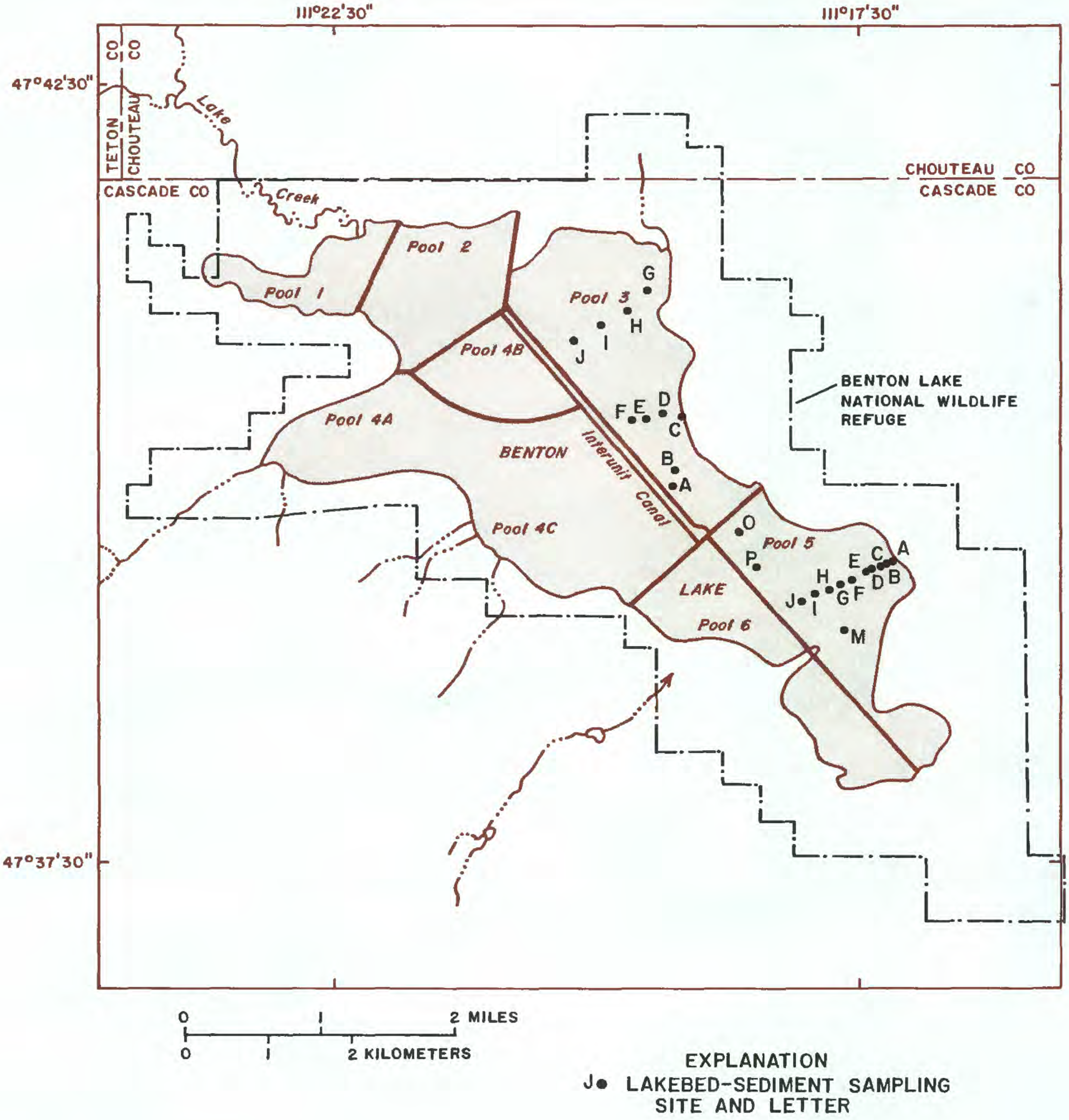


Figure 28. Lakebed-sediment sampling sites in Benton Lake Pools 3 and 5, west-central Montana.

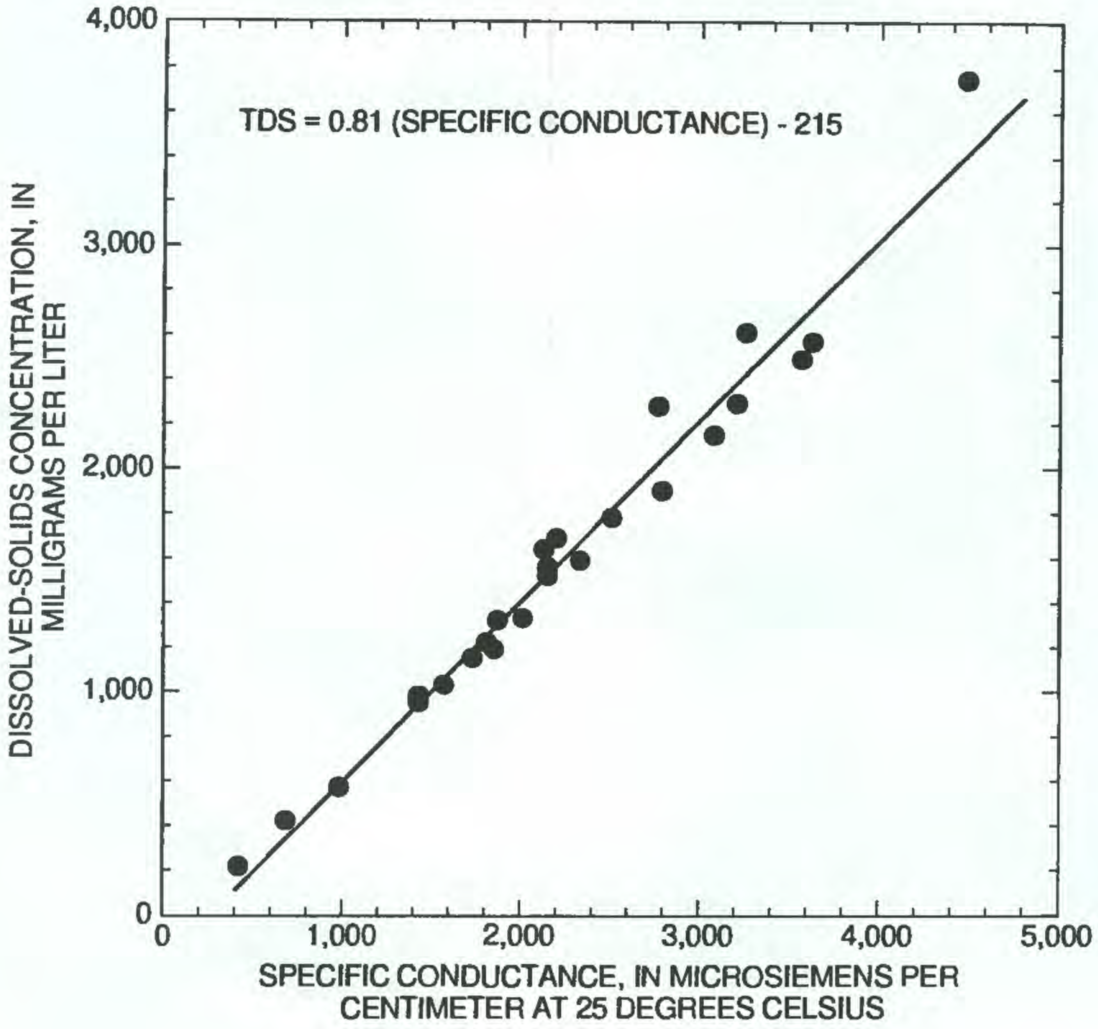


Figure 29. Relation of dissolved-solids (TDS) concentrations and specific-conductance values in water extracts of lakebed sediment, Benton Lake Pools 3 and 5, west-central Montana.

Table 11. Dissolved-solids concentrations computed from specific-conductance values of 5:1 water extracts of lakebed-sediment samples collected from the upper 3 inches of Benton Lake Pool 3, Montana

Sample site in Pool 3 (fig. 28)	Dissolved-solids concentration, in milligrams per liter[1]		
	Sample-collection date		
	04-22-92	09-03-92 or 09-25-92	Difference
A	580	507	-73
B	1,280	1,150	-130
C	348	879	+531
D	846	1,420	+574
E	2,680	[2]1,310	-1,370
F	1,130	1,430	+300
G	[2]2,060	[2]2,520	+460
H	[2]2,390	2,860	+470
I	2,730	[2]3,340	+610
J	1,410	2,530	+1,120

[1] Dissolved-solids (TDS) concentration determined using regression equation: TDS = 0.81 (specific conductance) - 215.
[2] Average of field replicates.

Table 12. Dissolved-solids concentrations computed from specific-conductance values of 5:1 water extracts of lakebed-sediment samples collected from the upper 3 inches of Benton Lake Pool 5, Montana

Sample site in Pool 5 (fig. 28)	Dissolved-solids concentration, in milligrams per liter[1]		
	Sample-collection date		
	6-12-92	09-03-92	Difference
A	1,440	399	-1,041
B	1,820	1,010	-810
C	1,150	676	-474
D	1,550	1,430	-120
E	1,610	1,620	+10
F	2,280	968	-1,312
G	2,480	2,120	-360
H	2,390	1,490	-900
I	2,350	1,330	-1,020
J	2,000	1,090	-910
M	4,350	3,250	-1,100
O	2,830	2,330	-500
P	1,670	2,130	+460

[1] Dissolved-solids (TDS) concentration determined using regression equation: TDS = 0.81 (specific conductance) - 215.

this mechanism was collected. However, refuge staff have reported seeing surficial lakebed material being blown off dry lakebeds by wind (Stephen J. Martin, oral commun., 1994) and one episode in April 1996 was photographed (fig. 30). The median decrease of 810 mg/L represents a decrease in soluble salts of 0.095 lb/ft^2 in the surficial lakebed sediments. Vertical movement of moisture potentially could affect the soluble-salt content in the surficial sediments. However, when the lakebed is dry, solutes would be expected to move upwards by capillary action as moisture is lost to evaporation, so the likelihood is minimal that the decreased concentrations resulted from downward migration of salts induced by infiltration of rain.

Redissolution of Salts

One possible reason that dissolved-solids concentrations have not increased substantially in Pools 3-6 at Benton Lake is that the precipitation-dissolution chemistry of carbonate minerals results in accumulation of carbonate minerals in lakebed sediment. The carbonate minerals that form as lake water evaporates do not readily or completely redissolve when a pool is refilled. Carbonate minerals are relatively insoluble, especially compared to magnesium and sodium sulfates. Therefore, when a pool is refilled with natural runoff, the inflowing water becomes saturated with respect to carbonate minerals after only a portion of the available carbonates dissolve. The remaining carbonate minerals in the lakebed do not dissolve. When a pool is refilled with pumped water, no carbonates dissolve because pumped water is saturated or oversaturated with respect to carbonate minerals based on saturation indices calculated by WATEQ4F (Ball and Nordstrom, 1987). Carbonate minerals constitute a portion of the salts precipitated from lake water (table 10). Laboratory experiments and saturation-index analysis were performed to explore the possible role of carbonate minerals in sequestering dissolved solids.

The precipitated salts (Salt 1 and Salt 2, table 10) collected in the evaporation experiment were used in additional experiments to determine what happens to these salts when mixed with water. In particular, these experiments were designed to determine the relative amount of carbonate and sulfate minerals that would redissolve. The two salt samples were mixed with either deionized water or Pool 3 water collected September 1, 1993. In the experiments, 4 g of salt were added to 1,000 mL water. This salt-to-water ratio was used to approximate the dissolved-solids concentration (4,090 mg/L) in the original lake water. The solutions were periodically shaken for 2 weeks, decanted, filtered, and analyzed for dissolved constituents. The concentrations of major ions in the final solution were compared to the original lake-water composition to see which constituents did or did not reappear (table 13).

The final dissolved-solids concentrations (2,760 and 2,910 mg/L) in solutions from the two experiments were 67 and 71 percent of the original dissolved-solids concentration of the evaporated lake water. These lower dissolved-solids concentrations could have been caused by several mechanisms. First, some of the precipitated minerals in Salt 1 and Salt 2 were hydrated (table 10). Upon dissolution, the water in these

Figure 30. Photographs of Benton Lake Pool 6, west-central Montana, showing dust cloud generated by wind erosion of lake-bed sediment on April 24, 1996 (top) and, for comparison, during calm conditions on June 4, 1996 (bottom). The average wind speed at Great Falls on April 24, 1996, was 27.1 miles per hour with a peak of 53 miles per hour (D.C. Williamson, National Weather Service, oral commun., 1996). Photographs are looking south and were taken from the Pool 5/6 dike by Mindy L. Meade, Benton Lake National Wildlife Refuge.

Table 13. Water-quality data for aqueous solutions from evaporation and redissolution experiments

[Constituents are dissolved. Abbreviations: g, grams; µS/cm, microsiemens per centimeter at 25 °Celsius; mg/L, milligrams per liter; mL, milliliters]

Constituent	Lake water evaporated to produce Salt 1 and Salt 2[1]	Experiment 1: Salt 1 plus deionized water[2]	Experiment 2: Salt 2 plus deionized water[3]	Lake water used in experiment 3[4]	Experiment 3: Salt 2 plus lake water[5]	Difference[6]
Specific conductance (µS/cm)	5,200	3,660	3,470	2,700	5,620	2,920
Calcium (mg/L as Ca)	62	17	14	110	130	20
Magnesium (mg/L as Mg)	340	220	220	170	360	190
Sodium (mg/L as Na)	840	560	520	300	830	530
Potassium (mg/L as K)	23	10	14	12	28	16
Alkalinity (mg/L as $CaCO_3$)	555	225	138	203	304	101
Sulfate (mg/L as SO_4)	2,300	1,900	1,800	1,400	3,000	1,600
Chloride (mg/L as Cl)	190	70	110	58	160	102
Dissolved solids, calculated (mg/L)	4,090	2,910	2,760	2,170	4,690	2,520

[1] Water collected from Benton Lake Pool 3 on June 1, 1993, and evaporated to dryness. Salts produced were used in experiments 1-3.

[2] Experiment 1: Mixture of 4 g Salt 1 from evaporated water plus 1,000 mL deionized water.

[3] Experiment 2: Mixture of 4 g Salt 2 from evaporated water plus 1,000 mL deionized water.

[4] Water collected from Benton Lake Pool 3 on September 1, 1993.

[5] Experiment 3: Mixture of 4 g Salt 2 from evaporated water plus 1,000 mL water collected from Benton Lake Pool 3 on September 1, 1993.

[6] Difference in concentration between lake water (column 5) and experiment 3 water.

minerals would not contribute dissolved solids to the final solution. For example, konyaite [$Na_2Mg(SO_4)_2 \bullet 5H_2O$] and bloedite [$Na_2Mg(SO_4)_2 \bullet 4H_2O$] occurred in one or both salt samples and are 26 and 12 percent water by weight, respectively. Mirabilite ($Na_2SO_4 \bullet 10H_2O$) and epsomite ($MgSO_4 \bullet 7H_2O$) are 56 and 60 percent water by weight; if these minerals had been part of the precipitate, the amount of water in Salt 1 and Salt 2 would have been greater. The recovery of sulfate was 78 and 83 percent by weight in the two samples. Assuming that all the sulfate minerals dissolved, the precipitate probably contained about 20 percent water.

The recovery of other major ions in experiments 1 and 2 was less than that for sulfate, probably for several reasons. Recovery of calcium and alkalinity was 23-41 percent by weight. These low recoveries probably were caused by incomplete dissolution of magnesium-calcium carbonate minerals. Saturation indices calculated by WATEQ4F (Ball and Nordstrom, 1987) for the final solutions show that the solutions were oversaturated with respect to carbonate minerals (table 14), and that, therefore, additional dissolution of carbonate minerals would not be expected. Chloride recovery was 37 and 58 percent. This low recovery probably was a result of underrepresentation of halite (NaCl) in the precipitate samples. Salt 2, collected from the middle of the evaporation beaker, had more chloride (and presumably halite) than Salt 1, which was collected from the top of the beaker. Most of the halite that would have precipitated probably formed at the bottom of the evaporation beaker as the last water evaporated. Recovery of sodium and magnesium was 62-67 percent. Recovery of sodium may have been reduced because of the underrepresentation of halite in the precipitate that was dissolved. Recovery of magnesium may have been reduced because some of the magnesium probably was in carbonate minerals that did not dissolve.

In experiment 3, 4 g of Salt 2 were dissolved in 1,000 mL lake water collected from Pool 3. The composition of the lake water and the final solution in experiment 3 are in table 13. Recovery was calculated by first determining the difference in concentration between the final solution and the added lake water (last column in table 13). This difference represents the solutes added by dissolution of the precipitate. Then, this difference was divided by the concentration in the original evaporated lake water to determine recovery. Recoveries of most constituents were similar to the recoveries in experiments 1 and 2, indicating that starting with water already containing solutes did not substantially inhibit dissolution of most of the minerals in the precipitate. Recovery of alkalinity was suppressed the most, probably because the added lake water was already partially saturated with a magnesium-calcium carbonate mineral.

Other Processes

Dissolved solids in pore water in lakebed sediment potentially could move vertically, either by move-

Table 14. Saturation indices of selected minerals in aqueous solutions from evaporation and redissolution experiments

[Abbreviations: g, grams; mL, milliliters]

Mineral	Salt 1 plus deionized water[1]	Salt 2 plus deionized water[2]	Salt 2 plus lake water[3]	Lake water[4]
Calcite [$CaCO_3$]	1.03	0.74	1.53	1.18
Dolomite [$CaMg(CO_3)_2$]	3.46	2.96	3.77	2.82
Magnesite [$MgCO_3$]	1.94	1.73	1.76	1.15
Hydromagnesite [$MgCO_3 \cdot H_2O$]	1.86	.83	-0.71	-4.14
Nesquehonite [$MgCO_3 \cdot 3H_2O$]	-0.47	-0.68	-0.66	-1.26
Huntite [$Mg_3Ca(CO_3)_4$]	4.23	3.30	4.17	1.99
Gypsum [$CaSO_4 \cdot 2H_2O$]	-1.54	-1.61	-0.59	-0.74
Epsomite [$MgSO_4 \cdot 7H_2O$]	-2.61	-2.61	-2.34	-2.75
Thenardite [Na_2SO_4]	-5.41	-5.49	-5.00	-8.31
Mirabilite [$Na_2SO_4 \cdot 10H_2O$]	-4.38	-4.46	-3.98	-5.02
Halite [NaCl]	-6.09	-5.93	-5.60	-6.43

[1]Mixture of 4 g Salt 1 from evaporated water plus 1,000 mL deionized water.
[2]Mixture of 4 g Salt 2 from evaporated water plus 1,000 mL deionized water.
[3]Mixture of 4 g Salt 2 from evaporated water plus 1,000 mL water collected from Benton Lake Pool 3 on September 1, 1993.
[4]Water collected from Benton Lake Pool 3 on September 1, 1993.

ment of the pore water or by diffusion through pore water if hydraulic or concentration gradients were present (Kadlec, 1982). No experiments were conducted to determine the role of these mechanisms. When a lakebed is dry, pore water moves upward by capillary action as evaporation occurs at the lakebed surface. This movement would bring dissolved solids to the surface, where they could precipitate and possibly be removed by wind erosion. When a pool is flooded, the hydraulic gradient and direction of water movement is downward. Because Pools 3-6 are flooded seasonally, pore water moves in both directions, but the direction of net solute movement is unknown. Similarly, diffusion can cause seasonal solute movement in both directions. Solutes would move down when surficial salinity in sediment is high due to evapoconcentration and would move up when surficial salinity is lowered by flooding with relatively fresh water.

Some ions may be removed or isolated from the system by chemical processes (Eugster and Jones, 1979). Degassing is a potential removal mechanism. Bicarbonate ions could be removed by the reaction

$$2HCO_3^- = CO_3^{2-} + CO_2 + H_2O.$$

This reaction is enhanced by the decrease in solubility of CO_2 with increased salinity. Bacterial reduction could cause loss of sulfate through degassing of H_2S or precipitation of insoluble iron sulfides. Sorption of sulfate on sediment surfaces is another potential isolation mechanism. The importance of these processes is not known.

IMPLICATIONS FOR MANAGEMENT OF WATER-BIRD HABITAT AT BENTON LAKE NATIONAL WILDLIFE REFUGE

Goals for salinity management at Benton Lake NWR are to maintain specific conductance at values less than 6,000 µS/cm in each of the refuge marsh units and less than 5,000 µS/cm in all units combined when water levels are at planned capacity in any given year (Donald G. Hultman, written commun., 1991). The first salinity goal for individual units has been attained in all but a few years since 1974. As indicated by the 22-year record of specific conductance (fig. 25), values greater than 6,000 µS/cm were measured in 1 year in Pools 1-2 and in 2-5 years in Pools 3-6. Commonly these exceedances occurred when the pool contained little water. Exceedances may appear to have occurred more frequently in 1990-95 than in earlier years because monitoring efforts were more comprehensive in these years. The second salinity goal of overall salinity maintenance for combined units has not been evaluated but probably has been attained routinely because the first goal, which is considered more conservative, has been attained most of the time.

However, specific-conductance values greater than 6,000 µS/cm occur routinely in some isolated parts of Benton Lake. Areas that receive intermittent or perennial inflow from natural runoff and parts of pools that are ponded when water levels are low frequently contain water with high specific conductance. Examples of these kinds of areas include Pool 1 near the mouth of Lake Creek, the borrow ditches in Pools 4C and 6 near the saline seep, parts of each pool that are far from the sites where fresh water is added, and Pool 4A, which receives water from an intermittent tributary. These areas generally are small and may not be significant in terms of the entire refuge. Dissolved-solids concentrations could be reduced by constructing facilities that could divert water from Lake Creek or the main part of Benton Lake to these areas.

As determined in this study, dissolved-solids concentrations do not appear to be increasing over time. If dissolved-solids concentrations are increasing, the rate of increase is small enough to be masked by the variability that occurs both seasonally and over multiyear periods. On the basis of this conclusion, major changes in management of the refuge may not be warranted because current dissolved-solids concentrations meet the goals for salinity management. However, understanding why dissolved-solids concentrations have not increased is important in order that management changes that may be considered in the future can be evaluated for their potential effect on dissolved solids in Benton Lake.

Water management and lakebed sediment are important in salt accumulation and removal in Pools 3-6 because these pools are repeatedly filled with water and allowed to partially or completely dry. The dissolved solids in lake water precipitate on or in the lakebed as the water evaporates. These precipitates are then either removed during dry periods, redissolved in pool water after refilling, or stored in the sediment as insoluble salts. Repeated sampling and testing of lakebed sediments in Pools 3 and 5 during the course of filling and drying demonstrated that leaving lakebeds dry and exposed to wind can reduce the soluble-salt content of the lakebed. Pool 3 was flooded all summer and the content of soluble salts in the lakebed increased as evaporation progressed and the pool volume decreased. In contrast, Pool 5 was dry for much of the summer, and the content of soluble salts in the lakebed decreased, presumably due to wind erosion. Clearly, the way water is managed is important in whether soluble salts accumulate or are removed. Therefore, the current management of seasonal flooding and drying of Pools 3-6 is a strategy that appears to be successful in managing salinity. If these pools were flooded continuously and no outlet were constructed, dissolved-solids concentrations levels would be expected to increase as the water added each year evaporated.

Before 1990, one salinity-control strategy used at the refuge was to move as much saline, evapoconcentrated water as possible from Pools 3, 5, and 6 to Pool 4C, where water-quality goals were sacrificed so that dissolved-solids concentrations in the other pools could be maintained more easily at optimum levels. This strategy may have helped reduce dissolved-solids concentrations in Pools 3, 5, and 6 but may not have been necessary. Current management that allows seasonal drying in each pool every 1-3 years is probably an effective way to deal with dissolved solids.

Consideration has been given by the USFWS to two structural changes (Donald U. Palawski, U.S. Fish and Wildlife Service, oral commun., 1994). The first proposed change is to construct an outlet canal at the east end of Benton Lake so saline water could be flushed from the lake. The feasibility of such a project likely would be constrained by its cost and by regulatory concerns about discharge of saline water to downstream wetlands and the Missouri River. The second proposal is to replace the pump station with a siphon constructed across the Muddy Creek valley to supply irrigation drainage directly from the Greenfields Bench. Once in place, the siphon potentially could supply more water more inexpensively than the current pump station. The probable effect on dissolved-solids concentrations of supplying irrigation drainage through a siphon will depend on other management practices. If the volume of imported irrigation-drainage water is greater than that previously supplied by pumping, then the dissolved-solids load delivered to Benton Lake will increase. In addition, with the availability of additional water, Pools 3-6 may not be left dry for as long as they are currently, and, therefore, the mechanisms that remove or isolate dissolved solids may not be as effective. If, however, both the siphon and outlet canal were constructed, all pools in Benton Lake could be operated as flow-through units and dissolved-solids concentrations could be managed. Also, water released through the outlet canal potentially could have relatively low dissolved-solids concentrations and regulatory concerns may be minimal.

Importing additional irrigation-drainage water from the Greenfields Bench will increase selenium loading to Benton Lake and possibly increase the selenium hazard to biota. Dissolved selenium entering the lake is quickly sequestered in bottom sediment and is bioaccumulated in aquatic plants, invertebrates, and water birds (Nimick and others, 1996; Zhang and Moore, 1996, 1997b, in press, a). This process of selenium removal from solution occurs rapidly enough that selenium probably could not be flushed from the lake through an outlet canal.

The dissolved solids and selenium delivered to Benton Lake come from nonpoint sources in the basin. Changes in land use and land management in the Benton Lake basin have the potential to reduce the loading of dissolved solids and selenium to Benton Lake. Dissolved-solids loading could be reduced in two ways. Changes in farming practices, as implemented at the Benton Lake saline-seep study site, can reduce the size of saline seeps (Miller and others, 1981) and presumably could reduce the discharge of dissolved solids to basin tributaries. However, no information is available to quantify the relation between reduction in the number and size of saline seeps and the resulting quality of surface water in a basin. A second way to reduce dissolved-solids loading is to reduce the volume of natural runoff. Reduction of runoff from spring and summer rainstorms would be particularly effective because the dissolved-solids concentrations are higher in rain-induced runoff than in snowmelt runoff. Runoff could be reduced by increasing the amount of land that is covered with perennial vegetation. Any reduction in dissolved-solids loading would occur only as long as the new land use is maintained. Also, the land-use change probably would need to be conducted in a relatively large part of the basin to produce a significant impact.

The two subsurface agricultural drainage systems that enhance flow at sites S-12 and S-14 discharge significant quantities of dissolved solids and, more importantly, selenium (table 9). Dismantling these systems has the potential to permanently improve water quality in the basin.

Long-term monitoring has provided the data necessary to assess hydrologic and water-quality trends in the basin and at Benton Lake NWR. Continued monitoring can provide data to assess future trends and the effectiveness of any efforts made in the basin to improve water quality.

SUMMARY AND CONCLUSIONS

The hydrology and water chemistry of the Benton Lake basin was studied in 1991-96 as part of a multi-agency study designed to develop a better understanding of the sources and processes that control the movement of dissolved solids and selenium in the basin and, more specifically, their fate in Benton Lake NWR. Dissolved solids and selenium potentially could adversely affect aquatic organisms and waterfowl at Benton Lake.

The Benton Lake basin is underlain primarily by the Cretaceous Colorado Group and Pleistocene glacial and alluvial deposits. Ground water in the basin has poor quality and is not extensively developed as a water supply. Shallow ground water contained high concentrations of major ions and nitrate. Selenium concentrations in most samples were elevated, ranging from 0.8 to 300 µg/L. Ground water typically was acidic because of oxidation of pyrite contained in shale and the lack of geologic materials to provide carbonate or other buffering.

Saline seeps are common in the Benton Lake basin. The number and size of saline seeps probably have increased during the past 50 years because of the crop-fallow rotation commonly used on farm land in the basin. Mapping identified more than 240 seeps, mostly in the south and west part of the basin in areas underlain by rocks of the Colorado Group. Water in seeps was saline, with specific-conductance values ranging from 5,900 to 27,500 µS/cm. Selenium concentrations ranged from 2 to 500 µg/L. Salts and selenium are stored in surface salts at the seeps and eventually are transported to basin streams and Benton Lake by natural runoff.

A saline seep near the south shore of Benton Lake was chosen by the USFWS and MSCA in 1990 for study and a pilot reclamation program. Test wells were installed upgradient from the seep in 1990. Water levels measured in the wells were used to define the recharge area for the seep. Part of the recharge area that had been farmed since at least 1941 using a crop-fallow rotation was planted in 1991 with alfalfa, which is a deep-rooted plant capable of reducing deep percolation of precipitation. Water-level declines since 1991 of as much as 4 ft in wells in and downgradient from the alfalfa field indicate that the alfalfa may be reducing discharge of saline and seleniferous ground water at the seep.

Tributaries to Lake Creek and Benton Lake are primarily ephemeral. Measured streamflow in tributaries was 0.3 ft^3/s or less except during snowmelt or precipitation runoff. Water in basin tributaries was saline. Specific-conductance values were high, ranging from 2,190 to 15,000 µS/cm. Selenium concentrations in tributaries varied significantly. Concentrations in samples from two tributaries that receive water from agricultural drainage systems and one saline seep along the south shore of Benton Lake were high, ranging from 320 to 3,000 µg/L. Concentrations in five other tributaries were much lower, ranging from <1 to 32 µg/L. Selenium concentrations varied proportionately with nitrate concentrations, indicating that selenium mobilization in the basin might be associated with agriculture.

Lake Creek is the major tributary to Benton Lake. Streamflow consists of natural runoff and irrigation drainage pumped from Muddy Creek. During 1991-92 and 1994-95, when precipitation was below or near normal, most (81-98 percent) of the streamflow in Lake Creek was pumped from Muddy Creek. In 1993, natural runoff in Lake Creek was greater and the amount of pumped water was reduced because of above normal precipitation.

Water quality in Lake Creek is variable, depending on whether streamflow is derived from pumped water, runoff during high-flow conditions, or runoff during base-flow conditions. Typically, specific-conductance values are high when streamflow is low and low when streamflow is high. Specific conductance was measured with an hourly recording meter at the Lake Creek gage from March 1992 through September 1995 during the ice-free season. Snowmelt runoff had mean-daily specific-conductance values as low as 322 µS/cm. Precipitation runoff had higher specific-conductance values, with minimum values during peak flow typically between 2,500 and 5,000 µS/cm. During low-flow conditions, specific-conductance values ranged from 2,740 to 14,000 µS/cm. Specific-conductance values of pumped water ranged from about 600 to 2,000 µS/cm.

Pumped water in Lake Creek was a magnesium bicarbonate type water. Selenium concentrations ranged from <1 to 10 µg/L, with a median of 3 µg/L. Discharge-weighted mean constituent concentrations in pumped water were similar to the median concentrations measured in samples because the quality of pumped water is relatively constant through time.

Natural runoff was a magnesium-sodium sulfate type water. Natural runoff generally was acidic, with pH values ranging from 5.1 to 8.0. Selenium concentrations ranged from 2 µg/L during snowmelt runoff to 220 µg/L during base-flow conditions, with a median concentration of 74 µg/L. Most median concentrations of major ions and selenium in samples were much higher than the estimated discharge-weighted mean concentrations because many samples were collected during low-flow periods. Natural flows in Lake Creek are high infrequently but provide large volumes of relatively dilute precipitation or snowmelt runoff to Benton Lake.

Constituent loads to Benton Lake were determined from daily mean streamflow and specific conductance measured at the Lake Creek gage and relations between specific conductance and constituent concentrations in periodic water samples. The dissolved-solids load during 1991-95 water years was 41,416 tons with 52 percent derived from pumped water. Annual totals in 1991-92 and 1994-95 ranged from 5,440 to 7,510 tons. Most (60-79 percent) of the dissolved solids was derived from pumped water in these years. In 1993, when precipitation was above normal, the annual dissolved-solids load (15,109 tons) was higher and the proportion (16 percent) derived from pumped water was much less. Estimates for 1970-94 indicate that dissolved-solids loading in natural runoff from the Benton Lake basin is greater than that measured in 1991-95 and that natural runoff is the major long-term source of dissolved solids. The long-term mean annual dissolved-solids load from natural runoff was 8,106 tons, which is about 2 times the mean annual load measured in 1991-95.

The relative proportions of alkalinity versus sulfate plus chloride in water flowing into Benton Lake are important because the evaporative salts produced from alkalinity are less soluble than the salts formed from sulfate and chloride. The anion load in natural runoff consists almost entirely of sulfate, whereas pumped water contains roughly equal amounts of sulfate and alkalinity. In dry years when inflow is primarily pumped water, Benton Lake receives a large amount of alkalinity. In wet years, when little or no water is pumped from Muddy Creek, almost no alkalinity is delivered. During 1991-95, alkalinity constituted an average of 23 percent of the total anion load.

The total selenium load entering Benton Lake in 1991-95 was 661 lb. On average, pumped water, which represented 75 percent of the total water volume, delivered 64 lb/yr, or 48 percent of the 1991-95 mean annual load. The selenium load in natural runoff was 52 percent of the 1991-95 total load, although natural flow accounted for only 25 percent of the flow entering Benton Lake. Selenium loading was highest in 1993, the one wet year during the study. Similar to dissolved solids, estimates for 1970-94 indicate that selenium loading in natural runoff from the Benton Lake basin may be greater than demonstrated by the 1991-95 data. The long-term mean annual selenium load from natural runoff was 137 lb, which is about 2 times the mean annual load measured in 1991-95.

Tributaries in the basin have a wide range of selenium concentrations but a relatively narrow range of specific-conductance values, indicating that all tributaries supply dissolved solids to Lake Creek but only a few supply selenium. Two tributaries that have perennial flow supplied by subsurface agricultural drainage from non-irrigated wheat fields appear to be significant sources of selenium in the Benton Lake basin. The selenium load in each is more than 3 times higher than the load carried by Lake Creek. Graphical analysis of water-quality data shows that the selenium in natural runoff in Lake Creek possibly is supplied largely by the older of the two drainage systems. The newer drainage system was installed in 1993, and increased selenium discharge from this site may not be apparent yet in downstream areas of the basin.

Benton Lake is a closed basin. Annual volumes of natural runoff from the Benton Lake basin were highly variable, ranging from 0 to 19,200 acre-ft in 1970-94. Mean annual natural runoff was 3,349 acre-ft. Annual volumes of pumped water ranged from 0 to 9,079 acre-ft, with a mean of 4,339 acre-ft. The mean annual volume of natural runoff to Benton Lake during 1991-95 was only 49 percent of the long-term mean, whereas the volume of pumped water was about 114 percent of the 1970-94 value.

Specific-conductance values in Pools 1 and 2 generally were less than 3,000 µS/cm. Specific-conductance values remained relatively constant and generally were lower than in Pools 3-6 because of the effect of inflows from Lake Creek and the flow-through operation of Pools 1-2. In contrast, evapoconcentration causes large variations in specific conductance in Pools 3-6, which are the terminal basins in Benton Lake and are flooded only seasonally. Values as high as 7,000 to 10,000 µS/cm were attained occasionally when pools had little water. The water type in Benton Lake generally is magnesium-sodium sulfate. When large amounts of pumped water have been added, bicarbonate becomes a dominant ion with sulfate.

Selenium concentrations in Benton Lake ranged from <1 to 4 µg/L, with a median of <1 µg/L. As selenium is added to Benton Lake, it is removed from solution and sequestered in bottom sediment and biota owing to biogeochemical processes.

Dissolved-solids accumulation in Benton Lake would be expected to be most pronounced in Pools 3-6. However, dissolved solids do not appear to be accumulating in these pools. If dissolved-solids concentrations are increasing in Pools 3-6, the rate of increase is small enough to be masked by the variability that occurs seasonally and over multiyear periods. If all dissolved solids estimated to have been delivered to Benton Lake between 1961-95 were still in solution in Pools 3-6, the specific conductance of lake water would be 26,100 to 71,400 µS/cm if the pools were full. Specific-conductance values in this range have not been measured in Benton Lake. Specific-conductance data collected from 1974-94 show that specific-conductance values vary from year to year and that trends of increasing and decreasing specific conductance are persistent over multiyear periods. However, no significant trend of increasing specific conductance is apparent in the 1974-95 record.

Salts probably are removed from Pools 3-6 by the following mechanisms. First, on the basis of minerals identified by XRD, the salts that precipitate in lakebed sediment as lake water evaporates are primarily sulfates and carbonates with sulfates being more abundant than carbonates. These salts form in the surficial lakebed sediment. Second, on the basis of inventories of soluble-salt content of lakebed sediment, some of these salts are assumed to be removed by wind erosion when a lakebed is dry. Third, when a pool is reflooded, sulfate salts dissolve readily whereas only some of the carbonates dissolve, because the lake water becomes saturated with respect to the carbonates before all have dissolved. Therefore, carbonates become sequestered in the lakebed sediments but sulfates do not. This mechanism was demonstrated in laboratory experiments. Fourth, some solute movement into deeper lakebed sediments may occur by diffusion and advection.

Because dissolved-solids concentrations do not appear to be increasing, major changes in management of Benton Lake NWR may not be warranted to control salinity. The dissolved solids in lake water probably precipitate on or in the lakebed as the water evaporates. These precipitates are then either removed during dry periods, redissolved in pool water after refilling, or stored in the sediment as insoluble salts. Repeated sampling and testing of lakebed sediments in Pools 3 and 5 during the course of filling and drying demonstrated that leaving lakebeds dry and exposed to wind can reduce the soluble-salt content of the lakebed. Therefore, the current management of seasonal flooding and drying Pools 3-6 is a strategy that appears to be effective in managing salts. If these pools were flooded continuously and no outlet were constructed, dissolved-solids concentrations would be expected to increase as water added each year evaporated. If land-use changes were made in the Benton Lake basin, loading of dissolved solids and selenium has the potential to decrease. Changes that would be effective include reducing the size of saline seeps and increasing the amount of land with perennial vegetative cover. Removal of two agricultural drain systems potentially could reduce selenium loading to Benton Lake significantly.

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SUPPLEMENTAL DATA

Table 15. Ground- and surface-water sampling sites in the Benton Lake basin, Montana

[Symbol: --, not applicable]

Site number (fig. 2 or 7)	Corresponding site number (Knapton and others, 1988)	Corresponding site number (Lambing and others, 1994)	U.S. Geological Survey identification number[1]	Site name or local number
			GROUND-WATER SITES	
W-1	--	W-57	473738111190501	22N03E26CDCB01
W-2	--	W-53	473909111194502	22N03E22AACB02
W-3	--	--	473903111193303	22N03E22ADAB03
W-4	--	--	473855111194504	22N03E22ADCB04
W-7	--	--	473907111194607	22N03E22AACC07
W-8	--	--	473908111195308	22N03E22ABDB08
W-9	--	--	473851111195009	22N03E22DBAA09
W-10	--	--	473857111201110	22N03E22BDDA10
W-11	--	W-54	473902111194611	22N03E22ADBB11
W-12	--	--	473905111200312	22N03E22ABCC12
W-13	--	--	473859111195513	22N03E22ACAC13
W-14	--	W-55	473855111195814	22N03E22ACCD14
W-15	--	--	473852111200815	22N03E22CAAA15
W-16	--	--	473837111200816	22N03E22CDAA16
W-17	--	W-56	473842111201817	22N03E22CACD17
W-18	--	--	473852111201518	22N03E22CAAB18
W-19	--	--	473845111195819	22N03E22DBCA19
W-20	--	W-52	473828111243701	22N02E24DDDA01
W-21	--	W-51	474203111230001	23N03E32CCAD01
W-22	--	W-50	474301111360501	23N01E28DADD01
W-23	--	--	474106111320601	22N02E06CCCA01
W-24	--	--	474059111315701	22N02E07BBAA01
W-25	--	--	474038111320401	22N02E07BCDC01
W-26	--	--	474037111321101	22N02E07BCCB01
W-27	--	--	474049111321601	22N01E12AADD01
W-28	--	--	474058111321601	22N01E12AAAA01
			SALINE SEEP SITES	
S-3	25	--	473908111194501	Benton Lake (Pool 4) seep number 7 near Black Eagle
S-4	--	--	473908111194502	Benton Lake (Pool 4) seep number 6 near Black Eagle
S-5	--	--	473910111203201	Benton Lake (Pool 4) seep number 4 near Black Eagle
S-6	24	--	473917111210001	Benton Lake (Pool 4) seep number 2 near Black Eagle
S-7	--	--	473918111210301	Benton Lake (Pool 4) seep number 1 near Black Eagle
			STREAM SITES	
S-1	22	S-44	06090650	Lake Creek near Power
S-2	--	--	473833111192701	Tributary to Benton Lake (Pool 6) near Black Eagle
S-8	--	S-45	474002111232001	Tributary to Benton Lake (Pool 4) at mouth near Black Eagle[2]
S-9			473927111243001	Tributary to Benton Lake (Pool 4) above lake near Black Eagle
S-10	--	--	473825111245401	Tributary to Benton Lake (Pool 4) at county road near Black Eagle
S-11	--	--	474316111243001	Unnamed tributary number 3 to Lake Creek near Power
S-12	23	S-43	474101111303201	Tributary (Somerfeld drain) to Lake Creek near Power
S-13	--	--	474429111322201	Unnamed tributary number 2 to Lake Creek near Power
S-14	--	--	474101111354001	Unnamed tributary number 1 to Lake Creek near Power
S-15	--	--	474429111361101	Lake Creek near Interstate 15 near Power

Table 15. Ground- and surface-water sampling sites in the Benton Lake basin, Montana (Continued)

Site number (fig. 2 or 7)	Corresponding site number (Knapton and others, 1988)	Corresponding site number (Lambing and others, 1994)	U.S. Geological Survey identification number[1]	Site name or local number
STREAM SITES–Continued				
S-16	--	S-42	474304111360201	Muddy Creek diversion near Power
S-17	--	S-21	474136111420501	Muddy Creek at pump station near Power
BENTON LAKE SITES				
L-1	--	S-46	474130111221501	Benton Lake (Pool 1) near Black Eagle
L-2	26	S-47	474110111212001	Benton Lake (Pool 2) near Black Eagle
L-3	27	S-48	474015111193501	Benton Lake (Pool 3) near Black Eagle
L-5	30	S-49	473910111180001	Benton Lake (Pool 5) near Black Eagle
L-7	--	--	473937111185701	Inflow to Benton Lake (Pool 3) near Black Eagle
L-8	--	--	473935111185501	Inflow to Benton Lake (Pool 5) near Black Eagle

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[1] Fifteen-digit site-identification number is a unique identifier that represents the approximate latitude and longitude location of the site (first 13 digits), plus the sequence number (last 2 digits). Eight-digit station-identification number represents the standard USGS streamflow-gaging station numbering system wherein numbers increase in a downstream direction according to geographic location within the drainage basin.

[2] Previously published as Tributary to Benton Lake (Pool 4) near Power.

Table 16. Ground-water-quality data for the Benton Lake basin, Montana

[Constituents are dissolved, except as indicated. Analytical laboratory: MBMG, Analytical Division, Montana Bureau of Mines and Geology, Butte, Mont.; USGS, National Water Quality Laboratory, U.S. Geological Survey, Arvada, Colo. Abbreviations: ft, feet below land surface; °C, degrees Celsius; IT, incremental titration; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25 °C; mg/L, milligrams per liter; permil, parts per thousand; TU, tritium units. Symbols: --, no data; <, less than]

Site number (fig. 2 or 7)	Date	Analytical laboratory	Depth of well (ft)	Specific conductance, field (µS/cm)	pH, field (standard units)	Temperature, water (°C)	Calcium (mg/L as Ca)	Magnesium (mg/L as Mg)	Sodium (mg/L as Na)	Potassium (mg/L as K)
W-1	11-16-90	USGS	177	10,100	5.6	8.5	400	510	1,700	30
W-2	06-18-91	USGS	12	14,700	5.0	11.0	360	1,600	2,000	41
W-11	06-19-91	USGS	49	14,000	6.7	10.0	360	2,300	1,200	42
W-14	06-19-91	USGS	59	9,800	7.2	9.5	380	730	1,600	21
W-17	06-20-91	USGS	78	10,100	7.2	10.0	200	500	2,100	16
W-20	11-15-90	USGS	160	1,730	7.7	10.0	18	14	780	4.5
W-21	11-15-90	USGS	27	5,010	6.3	7.5	460	330	400	13
W-22	11-16-90	USGS	111	6,700	9.1	8.5	2.4	5.5	1,500	7.0
W-23	09-28-78	MBMG	19	8,730	6.3	12.0	39	130	190	15
W-24	09-28-78	MBMG	28	5,900	3.7	11.0	430	640	570	9.0
W-25	09-28-78	MBMG	32	6,060	3.8	9.0	440	480	490	8.0
W-26	04-15-76	MBMG[1]	27	4,690	4.2	6.0	430	590	340	7.0
	09-28-78	MBMG	27	5,700	4.1	9.0	450	640	370	7.0
W-27	09-28-78	MBMG	30	4,820	6.4	9.0	450	560	340	10
W-28	09-28-78	MBMG	23	6,750	6.0	12.0	430	800	650	8.0

Site number	Bicarbonate, field (IT) (mg/L as HCO_3)	Carbonate, field (IT) (mg/L as CO_3)	Alkalinity, field (IT) (mg/L as $CaCO_3$)	Alkalinity, laboratory (mg/L as $CaCO_3$)	Sulfate (mg/L as SO_4)	Chloride (mg/L as Cl)	Fluoride (mg/L as F)	Silica (mg/L as SiO_2)	Dissolved solids, calculated (mg/L)
W-1	125	0	102	94	5,600	330	2.9	29	9,250
W-2	95	0	78	3.8	12,000	210	17	29	16,300
W-11	741	0	608	607	13,000	210	.40	9.9	17,600
W-14	723	0	591	594	7,000	220	1.0	11	10,400
W-17	1,040	0	852	847	6,000	300	1.6	6.8	9,660
W-20	--	--	--	870	990	14	.80	7.2	2,350
W-21	147	0	121	122	2,900	180	1.8	19	4,560
W-22	1,860	132	--	1,720	1,600	39	1.4	2.9	4,210
W-23	310	0	255	98	840	36	1.2	1.6	1,420
W-24	0	0	0	0	4,900	210	2.9	70	6,950
W-25	0	0	0	0	4,800	320	.20	54	6,890
W-26	0	0	0	0	5,000	180	.30	52	6,750
	0	0	0	0	5,000	170	2.9	50	6,770
W-27	240	0	197	160	3,600	120	1.7	10	5,240
W-28	150	0	125	63	5,100	190	12	--	7,330

Table 16. Ground-water-quality data for the Benton Lake basin, Montana (Continued)

Site number	Nitrite (mg/L as N)	Nitrite plus nitrate (mg/L as N)	Iron (μg/L as Fe)	Manganese (μg/L as Mn)	Selenium (μg/L as Se)	Deuterium/ hydrogen stable isotope ratio (permil)	Oxygen 18/ oxygen 16 stable isotope ratio (permil)	Tritium (TU)
W-1	0.06	130	--	--	530	--	--	--
W-2	.04	1.7	130	21,000	300	-148.0	-18.25	12
W-11	.05	20	10	220	270	-129.0	-15.10	13
W-14	.03	13	10	320	200	-133.0	-16.00	2.5
W-17	.15	3.9	30	1,400	19	-132.0	-15.90	<.3
W-20	<.01	.50	--	--	<1	--	--	--
W-21	<.01	41	--	--	87	--	--	--
W-22	.01	<.1	--	--	1	--	--	--
W-23	--	2.8	220	70	.8	--	--	--
W-24	--	23	190	6,000	2	--	--	--
W-25	--	55	400	14,000	4	--	--	--
W-26	--	10	400	13,000	9	--	--	--
	--	7.7	1,900	13,000	5	--	--	--
W-27	--	5.4	80	1,700	2	--	--	--
W-28	--	21	80	2,300	43	--	--	--

[1] Analysis published in Miller and others (1980).

Table 17. Water-quality data for saline seeps, streams, and Benton Lake in the Benton Lake basin, Montana

[Constituents are dissolved, except as indicated. Abbreviations: °C, degrees Celsius; inst., instantaneous; μg/L, micrograms per liter; μS/cm, microsiemens per centimeter at 25 °C; mg/L, milligrams per liter; permil, parts per thousand. Symbols: <, less than; --, no data]

Site number (fig. 2)	Date	Discharge, inst. (cubic feet per second)	Specific conductance, field (μS/cm)	pH, field (standard units)	Temperature, water (°C)	Calcium (mg/L as Ca)	Magnesium (mg/L as Mg)	Sodium (mg/L as Na)	Potassium (mg/L as K)	Alkalinity, laboratory (mg/L as $CaCO_3$)
SALINE SEEP SITES										
S-3	06-06-86	<0.01	21,000	5.0	17.5	1,000	3,600	--	--	--
	06-02-94	<.01	21,300	4.7	--	--	--	--	--	--
S-4	06-02-94	.02	27,500	8.3	--	--	--	--	--	--
S-5	04-29-94	.02	17,300	8.5	16.0	--	--	--	--	--
S-6	06-05-86	<.01	6,700	8.0	20.0	440	450	--	--	--
	04-29-94	.03	8,460	8.5	6.5	--	--	--	--	--
	03-17-95	.01	5,900	8.2	3.5	--	--	--	--	--
	05-24-95	.01	7,320	8.3	11.5	440	400	990	11	405
S-7	06-02-94	.05	6,200	7.3	15.0	--	--	--	--	--
	05-24-95	.05	6,250	7.1	7.5	430	300	800	13	385
STREAM SITES										
S-2	04-29-94	.1	9,640	8.4	16.0	--	--	--	--	--
S-8	04-22-92	.3	12,500	8.5	15.0	450	1,200	1,800	19	494
	03-08-93	.5	4,150	7.9	7.5	190	290	540	11	247
	03-24-93	.6	8,970	8.4	14.0	310	660	1,300	16	380
	04-15-94	.15	14,400	8.3	13.0	460	1,200	2,000	14	687
	04-29-94	.3	13,100	8.2	16.0	--	--	--	--	--
	03-17-95	.16	10,000	8.4	10.0	--	--	--	--	--
	05-24-95	.01	14,600	8.7	22.5	--	--	--	--	--
S-9	03-17-95	.09	8,110	8.4	4.5	--	--	--	--	--
	05-24-95	.04	11,200	8.5	20.5	--	--	--	--	--
S-10	06-02-94	.1	10,700	8.3	10.5	--	--	--	--	--
S-11	04-29-94	.05	7,270	7.2	5.0	--	--	--	--	--
	06-08-95	--	2,190	4.5	10.0	81	210	100	8.9	0
S-12	06-06-86	.3	12,000	4.5	15.0	1,000	1,300	--	--	--
	11-16-90	.02	15,000	4.6	.5	--	--	--	--	--
	06-14-91	.3	13,000	4.5	15.0	--	--	--	--	--
	04-03-92	.1	12,300	4.6	9.5	390	1,100	1,300	11	1
	06-02-92	.1	14,000	4.4	20.0	380	1,200	1,600	16	1
	06-02-94	.2	11,400	4.9	12.0	450	1,300	1,600	13	<1
	03-17-95	.05	10,800	4.7	1.0	--	--	--	--	--
	06-05-96	.04	12,500	4.8	12.4	--	--	--	--	--
S-13	06-02-94	.01	9,340	3.6	13.0	--	--	--	--	--
	05-30-96	.2	4,260	4.1	17.7	--	--	--	--	--
S-14	06-02-94	.04	7,410	7.3	9.5	--	--	--	--	--
	03-17-95	.02	8,050	6.6	3.5	1,100	260	850	20	902
	05-24-95	.02	8,250	6.6	8.0	1,000	260	870	23	566
S-15	05-30-96	19	6,840	8.2	20.2	--	--	--	--	--
	06-03-96	.1	4,170	7.2	--	--	--	--	--	--
S-16	07-24-90	18	680	8.7	19.0	46	54	38	2.3	274
S-17	04-30-91	10	1,710	8.8	8.5	57	120	140	2.5	317
	05-28-92	100	635	8.5	16.5	43	43	27	1.9	224

Table 17. Water-quality data for saline seeps, streams, and Benton Lake in the Benton Lake basin, Montana (Continued)

Site number (fig. 2)	Sulfate (mg/L as SO_4)	Chloride (mg/L as Cl)	Fluoride (mg/L as F)	Silica (mg/L as SiO_3)	Dissolved solids, calculated (mg/L)	Nitrite (mg/L as N)	Nitrite plus nitrate (mg/L as N)	Selenium, dissolved (µg/L as Se)	Selenium, total recoverable (µg/L as Se)	Deuterium/hydrogen stable isotope ratio (permil)	Oxygen 18/oxygen 16 stable isotope ratio (permil)
SALINE SEEP SITES											
S-3	--	--	--	--	--	--	--	500	--	--	--
	--	--	--	--	--	0.16	46	320	--	--	--
S-4	--	--	--	--	--	.16	.29	10	--	--	--
S-5	--	--	--	--	--	.01	.06	2	--	--	--
S-6	--	--	--	--	--	--	--	15	--	--	--
	--	--	--	--	--	<.01	.89	24	--	--	--
	--	--	--	--	--	.03	3.7	51	--	--	--
	3,800	440	0.9	12	6,340	<.01	.07	7	--	-124.4	-15.47
S-7	--	--	--	--	--	.02	1.8	16	--	--	--
	3,200	320	.6	11	5,330	.01	5.2	13	--	-131.5	-15.83
STREAM SITES											
S-2	--	--	--	--	--	<.01	.13	<1	--	--	--
S-8	7,900	580	1.4	2.4	12,200	--	--	18	--	--	--
	2,400	140	.40	--	3,720	--	--	5	--	--	--
	4,700	340	.90	5.7	7,560	--	--	3	--	--	--
	9,200	600	.90	--	13,900	<.01	<.05	2	--	-119.0	-13.79
	--	--	--	--	--	<.01	.27	5	--	--	--
	--	--	--	--	--	.04	.14	14	--	--	--
	--	--	--	--	--	<.01	<.05	3	--	--	--
S-9	--	--	--	--	--	.05	.97	32	--	--	--
	--	--	--	--	--	<.01	<.05	7	--	--	--
S-10	--	--	--	--	--	.03	3.6	19	--	--	--
S-11	--	--	--	--	--	<.01	<.05	<1	--	--	--
	1,300	22	.70	13	1,740	--	--	5	--	--	--
S-12	--	--	--	--	--	--	--	580	--	--	--
	--	--	--	--	--	--	--	680	--	--	--
	--	--	--	--	--	--	--	--	660	--	--
	7,600	370	12	20	10,800	--	--	--	570	--	--
	8,400	400	16	21	12,000	--	--	--	730	--	--
	8,400	420	.20	--	14,000	.03	400	870	--	-109.0	-12.12
	--	--	--	--	--	.07	330	910	--	--	--
	--	--	--	--	--	--	--	640	--	--	--
S-13	--	--	--	--	--	.02	2.1	23	--	--	--
	--	--	--	--	--	--	--	14	--	--	--
S-14	--	--	--	--	--	.79	300	2,900	--	--	--
	2,200	700	.4	15	6,850	.55	260	3,000	--	--	--
	2,200	700	.4	15	6,700	.44	290	2,600	--	-130.5	-15.44
S-15	--	--	--	--	--	--	--	3	--	--	--
	--	--	--	--	--	--	--	2	--	--	--
S-16	110	5.2	.50	6.9	440	--	2.8	3	3	--	--
S-17	660	19	.90	2.2	1,210	<.01	4.9	7	8	--	--
	120	7.0	.60	5.8	383	--	--	--	2	--	--

Table 17. Water-quality data for saline seeps, streams, and Benton Lake in the Benton Lake basin, Montana (Continued)

Site number (fig. 2)	Date	Discharge, inst. (cubic feet per second)	Specific conductance, field (µS/cm)	pH, field (standard units)	Temperature, water (°C)	Calcium (mg/L as Ca)	Magnesium (mg/L as Mg)	Sodium (mg/L as Na)	Potassium (mg/L as K)	Alkalinity, laboratory (mg/L as $CaCO_3$)
				BENTON LAKE SITES						
L-1	04-08-92	--	1,740	9.1	.5	--	--	--	--	--
	06-23-92	--	815	9.4	27.0	--	--	--	--	--
L-2	08-12-86	--	2,880	9.8	18.0	100	170	--	--	--
	04-18-91	--	1,840	8.9	4.0	71	120	170	9.7	389
	07-03-91	--	1,380	10.2	21.5	43	97	140	3.9	161
	04-08-92	--	1,370	9.5	.5	42	110	120	6.9	312
	06-23-92	--	758	9.7	27.0	37	60	55	2.7	288
L-3	04-22-92	--	6,120	8.6	--	86	480	950	10	902
	06-23-92	--	1,730	9.3	29.0	79	110	170	9.9	459
	09-03-92	--	4,690	9.3	24.0	66	310	760	4.0	684
	09-24-92	--	7,360	9.2	13.0	51	540	1,200	23	1,190
	05-21-93	--	4,830	9.3	18.0	61	300	690	25	545
	06-01-93	--	5,200	9.3	19.0	62	340	840	23	555
	08-18-93	--	5,890	9.2	23.0	110	76	960	--	693
	09-01-93	--	2,740	8.7	18.5	110	170	300	12	203
	03-17-95	--	1,290	9.3	13.0	40	91	110	7.9	286
L-5	08-12-86	--	3,550	9.1	16.0	50	220	--	--	--
	04-18-91	--	4,600	9.0	4.0	61	340	660	24	411
	07-03-91	--	3,400	9.6	24.0	42	270	520	17	527
	04-08-92	--	9,150	9.3	.5	95	670	1,400	36	778
	09-24-92	--	1,260	8.8	13.0	53	86	86	15	396
	05-21-93	--	1,030	9.4	17.5	19	57	130	16	295
	08-18-93	--	1,520	9.3	22.0	39	63	230	9.6	550
	03-17-95	--	5,030	9.0	14.0	38	360	760	19	922
L-7	05-22-92	21	1,030	8.6	13.5	43	74	76	4.4	256
	05-29-92	--	752	10.0	15.5	21	57	58	3.4	177

Table 17. Water-quality data for saline seeps, streams, and Benton Lake in the Benton Lake basin, Montana (Continued)

Site number (fig. 2)	Sulfate (mg/L as SO_4)	Chloride (mg/L as Cl)	Fluoride (mg/L as F)	Silica (mg/L as SiO_3)	Dissolved solids, calculated (mg/L)	Nitrite (mg/L as N)	Nitrite plus nitrate (mg/L as N)	Selenium, dissolved (µg/L as Se)	Selenium, total recoverable (µg/L as Se)	Deuterium/hydrogen stable isotope ratio (permil)	Oxygen 18/oxygen 16 stable isotope ratio (permil)
BENTON LAKE SITES											
L-1	--	--	--	--	--	--	--	--	2	--	--
	--	--	--	--	--	--	--	--	1	-110.0	-13.35
L-2	--	--	--	--	--	--	--	1	--	--	--
	640	40	.90	<0.1	1,290	<.01	<.05	<1	<1	--	--
	640	20	.70	.50	1,040	<.01	<.05	4	4	-99.5	-12.30
	420	21	1.0	1.5	910	<.01	<.05	<1	<1	-100.0	-11.05
	170	10	1.0	5.8	516	.01	<.05	<1	<1	-107.0	-12.60
L-3	2,600	250	1.0	2.0	4,920	--	--	<1	--	--	--
	540	35	1.2	4.5	1,230	.01	<.05	<1	<1	-83.0	-8.05
	2,000	130	2.8	1.5	3,680	--	--	<1	--	-46.0	0
	3,100	270	1.3	.30	5,900	--	--	<1	--	-30.0	2.55
	2,200	170	2.3	.20	3,780	--	--	<1	--	-59.4	-2.94
	2,300	190	2.5	<.1	4,090	--	--	--	--	-59.9	-3.03
	2,500	270	2.9	4.7	--	--	--	--	--	-68.0	-4.48
	1,400	58	1.3	--	2,170	--	--	--	--	--	--
	400	26	1.2	.18	848	--	--	<1	--	--	--
L-5	--	--	--	--	--	--	--	<1	--	--	--
	2,400	180	1.2	<.1	3,910	<.01	<.05	<1	<1	--	--
	1,600	120	1.5	.90	2,890	<.01	<.05	1	1	-61.0	-5.20
	4,700	370	1.1	1.2	7,740	<.01	<.05	<1	<1	-53.0	-2.10
	290	33	1.0	.60	802	--	--	2	--	-105.0	-11.75
	220	36	1.1	.90	657	--	--	<1	--	-108.0	-10.95
	240	63	1.7	1.9	978	--	--	--	--	-73.8	-5.10
	2,000	170	2.4	3.2	3,910	--	--	<1	--	--	--
L-7	280	18	.80	.70	650	--	--	2	--	--	--
	220	11	.70	1.4	479	--	--	2	--	-114.0	-13.75

Table 18. Water-quality data for Lake Creek near Power (site S-1), Montana

[Constituents are dissolved, except as indicated. Abbreviations: °C, degrees Celsius; inst., instantaneous; e, estimated; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25 °C; mg/L, milligrams per liter; permil, parts per thousand. Symbols: --, no data; <, less than]

Date	Time	Discharge, inst. (cubic feet per second)	Specific conductance, field (µS/cm)	pH, field (standard units)	Temperature, water (°C)	Calcium (mg/L as Ca)	Magnesium (mg/L as Mg)	Sodium (mg/L as Na)	Potassium (mg/L as K)	Alkalinity, laboratory (mg/L as $CaCO_3$)
PUMPED WATER										
08-12-86[1]	1800	30	860	8.0	18.0	46	59	--	--	--
08-02-90	1250	34	776	8.3	19.0	46	52	44	2.6	257
06-14-91	1015	34	905	8.5	15.0	48	58	62	2.1	221
09-10-91	1100	37	665	8.6	12.0	43	48	31	2.2	253
05-22-92	1300	34	704	8.3	12.5	45	48	36	2.7	231
05-29-92	0730	35	679	8.4	14.5	45	45	33	2.0	223
09-03-92	1745	35	735	8.9	20.0	40	56	36	2.0	253
08-18-93	1210	26	1,090	8.3	14.5	54	75	76	3.1	259
05-20-94	0830	30	1,560	--	--	--	--	--	--	--
06-02-94	1520	30	910	8.5	17.5	48	60	63	2.0	228
08-16-94	1115	40	801	8.4	19.0	43	60	40	2.3	280
05-24-95	1440	23	1,890	8.8	16.0	--	--	--	--	--
PUMPED WATER THROUGH DRY CHANNEL										
07-25-90	1032	e5	17,300	4.5	17.0	300	940	2,500	27	1.0
07-25-90	1135	11	8,980	6.7	17.0	290	670	1,300	18	143
07-25-90	1230	15	4,000	7.2	17.0	180	270	460	11	205
07-25-90	1420	15	2,530	7.4	20.5	120	170	260	6.6	232
07-25-90	1955	16	1,710	7.9	19.5	71	110	140	4.9	252
07-26-90	0920	16	1,260	8.1	16.0	62	88	97	3.7	268
08-30-95[1]	0930	--	26,100	5.9	10.0	--	--	--	--	--
NATURAL RUNOFF										
11-16-90	1010	.07	9,600	6.5	1.0	--	--	--	--	--
04-03-91	0900	.18	6,950	5.9	5.0	230	610	850	8.8	7.0
04-18-91	1410	35	1,360	6.3	4.5	40	96	100	6.6	18
04-19-91	1250	7.6	2,280	6.4	7.0	--	--	--	--	--
04-30-91	1140	.30	9,600	5.2	6.5	290	960	1,300	15	3.0
06-21-91	1015	90	1,070	7.1	--	--	--	--	--	--
06-22-91	1000	30	2,000	6.8	--	--	--	--	--	--
11-26-91	0915	.05	9,250	6.2	0	--	--	--	--	--
03-05-92	1230	.30	8,160	--	2.0	--	--	--	--	--
03-19-92	1230	.26	11,000	5.1	5.0	--	--	--	--	--
04-04-92	0820	.13	11,600	6.6	7.5	390	1,000	1,600	10	27
04-22-92	1615	.55	13,700	5.3	14.0	440	1,400	1,800	14	6.5
03-06-93	1100	258	346	7.3	.5	16	15	22	7.5	35
03-08-93	1500	50	608	7.3	4.5	29	32	46	7.2	39
03-24-93	1630	3.0	2,740	7.2	15.0	83	180	300	11	44

Table 18. Water-quality data for Lake Creek near Power (site S-1), Montana (Continued)

Date	Sulfate (mg/L as SO_4)	Chloride (mg/L as Cl)	Fluoride (mg/L as F)	Silica (mg/L as SiO_3)	Dissolved solids, calculated (mg/L)	Nitrite (mg/L as N)	Nitrite plus nitrate (mg/L as N)	Selenium, dissolved (µg/L as Se)	Selenium, total recoverable (µg/L as Se)	Deuterium/hydrogen stable isotope ratio (permil)	Oxygen 18/oxygen 16 stable isotope ratio (permil)
					PUMPED WATER						
08-12-86	--	--	--	--	--	--	--	4	--	--	--
08-02-90	170	8.2	0.50	5.6	494	--	2.5	3	3	--	--
06-14-91	250	8.3	.70	5.3	577	0.01	2.3	2	3	--	--
09-10-91	120	8.4	.60	6.6	420	.01	1.9	2	2	--	--
05-22-92	130	8.3	.70	4.7	414	--	--	<1	--	--	--
05-29-92	120	6.7	.60	4.9	402	.02	2.4	3	2	-128.0	-16.95
09-03-92	140	10	.70	1.9	438	--	--	3	3	--	--
08-18-93	310	14	1.0	5.7	694	--	--	5	--	-126.0	-16.61
05-20-94	--	--	--	--	--	--	--	3	--	--	--
06-02-94	260	9.8	.60	--	589	.02	2.0	2	--	--	--
08-16-94	150	8.3	.90	5.7	489	.03	2.4	2	--	-128.0	-16.34
05-24-95	--	--	--	--	--	.03	4.1	7	10	--	--
					PUMPED WATER THROUGH DRY CHANNEL						
07-25-90	13,000	550	2.3	8.3	17,800	--	110	190	190	--	--
07-25-90	5,500	270	3.5	4.0	8,470	--	75	110	110	--	--
07-25-90	2,000	97	1.0	4.7	3,270	--	28	42	39	--	--
07-25-90	1,100	54	1.0	5.2	1,910	--	13	21	19	--	--
07-25-90	590	33	1.0	5.4	1,140	--	6.6	10	10	--	--
07-26-90	410	19	.90	6.1	865	--	3.9	6	5	--	--
08-30-95	--	--	--	--	--	--	--	--	--	--	--
					NATURAL RUNOFF						
11-16-90	--	--	--	--	--	--	--	160	--	--	--
04-03-91	4,300	280	2.5	5.1	6,630	.16	75	140	120	--	--
04-18-91	710	24	.70	6.5	1,020	.02	6.7	11	12	--	--
04-19-91	--	--	--	--	--	--	--	--	13	--	--
04-30-91	7,000	310	4.3	6.1	9,920	.17	5.9	61	62	--	--
06-21-91	--	--	--	--	--	--	--	--	14	--	--
06-22-91	--	--	--	--	--	--	--	--	11	--	--
11-26-91	--	--	--	--	--	--	--	--	90	--	--
03-05-92	--	--	--	--	--	--	--	--	84	--	--
03-19-92	--	--	--	--	--	--	--	--	110	--	--
04-04-92	7,600	380	1.0	6.5	11,300	.14	66	120	120	-116.0	-12.90
04-22-92	9,200	480	5.7	7.1	13,400	--	--	110	--	--	--
03-06-93	110	6.7	.20	--	198	--	--	3	--	--	--
03-08-93	250	8.1	.20	--	396	--	--	2	--	-177.0	-23.21
03-24-93	1,400	7.6	--	--	2,010	--	--	16	--	--	--

Table 18. Water-quality data for Lake Creek near Power (site S-1), Montana (Continued)

Date	Time	Discharge, inst. (cubic feet per second)	Specific conductance, field (µS/cm)	pH, field (standard units)	Temperature, water °C)	Calcium (mg/L as Ca)	Magnesium (mg/L as Mg)	Sodium (mg/L as Na)	Potassium (mg/L as K)	Alkalinity, laboratory (mg/L as $CaCO_3$)
					NATURAL RUNOFF--Continued					
04-09-93	1045	.82	6,410	6.1	6.5	180	500	800	14	14
05-21-93	1015	.36	9,280	8.0	17.0	360	790	1,100	13	66
06-01-93	1500	3.0	8,840	7.1	--	320	680	1,100	15	34
07-07-93	0930	.05	8,680	--	15.0	250	870	1,000	13	4.9
03-03-94	1323	e15	2,720	7.4	7.0	--	--	--	--	--
04-15-94	1000	.05	12,600	5.5	5.0	430	1,200	1,700	13	6.4
04-26-94	0925	3.0	11,200	5.1	1.5	--	--	--	--	--
04-26-94	1430	3.0	10,100	5.5	7.0	--	--	--	--	--
04-27-94	1530	13	7,800	--	9.5	--	--	--	--	--
04-28-94	0904	11	7,110	7.0	3.5	--	--	--	--	--
04-28-94	1135	10	7,180	--	8.0	--	--	--	--	—
04-28-94	1600	9.0	8,100	--	10.5	--	--	--	--	--
04-29-94	0835	8.0	8,980	--	3.0	--	--	--	--	--
04-29-94	1100	8.0	9,130	6.9	5.0	270	820	1,200	18	43
03-17-95	1230	.11	6,570	5.3	3.5	--	--	--	--	--

[1] Sample collected at mouth of Lake Creek.

Table 18. Water-quality data for Lake Creek near Power (site S-1), Montana (Continued)

Date	Sulfate (mg/L as SO_4)	Chloride (mg/L as Cl)	Fluoride (mg/L as F)	Silica (mg/L as SiO_3)	Dissolved solids, calculated (mg/L)	Nitrite (mg/L as N)	Nitrite plus nitrate (mg/L as N)	Selenium, dissolved (µg/L as Se)	Selenium, total recoverable (µg/L as Se)	Deuterium/ hydrogen stable isotope ratio (permil)	Oxygen 18/ oxygen 16 stable isotope ratio (permil)
					NATURAL RUNOFF--Continued						
04-09-93	3,900	130	2.2	4.0	5,540	--	--	46	--	-141.0	-17.15
05-21-93	5,700	210	3.7	1.2	8,220	--	--	110	110	--	--
06-01-93	5,200	220	2.5	2.4	7,560	--	--	57	--	-94.5	-8.48
07-07-93	5,700	210	2.5	4.8	8,050	--	--	47	--	--	--
03-03-94	--	--	--	--	--	--	--	30	--	--	--
04-15-94	9,000	470	.60	--	13,400	.07	130	220	--	-119.0	-13.05
04-26-94	--	--	--	--	--	--	--	110	--	--	--
04-26-94	--	--	--	--	--	--	--	160	--	--	--
04-27-94	--	--	--	--	--	--	--	170	--	--	--
04-28-94	--	--	--	--	--	--	--	78	--	--	--
04-28-94	--	--	--	--	--	--	--	62	--	--	--
04-28-94	--	--	--	--	--	--	--	55	--	--	--
04-29-94	--	--	--	--	--	--	--	110	--	--	--
04-29-94	6,100	190	1.6	--	8,860	.23	53	88	--	-126.0	-14.72
03-17-95	--	--	--	--	--	.14	43	69	--	--	--

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